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# Explosive Detection Equipment and Technology for Border Security

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BORDER SECURITY PROGRAMME

SENSORS, RADAR TECHNOLOGIES AND CYBERSECURITY UNIT

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# 1. Introduction

The detection of explosives at airports, land borders and seaports is an important area for preventing terrorism and organized crime. It forms one aspect of the general effort to prevent the transport of illicit materials, which includes also small arms, nuclear material and narcotics. A number of different methods of explosive detection have been developed in the past that can detect such material from a very small up to a very large quantity. Good, thorough reviews are already available (see References [1] – [6] and [24]). This survey is intended to provide a brief summary and to explain the role of European legislation and the European Commission's research programs in this field. It describes:

- Techniques of explosive detection that are in use and the latest techniques that are in development.
- Characteristics of explosives that are, or might be, used to provide a signature for exploitation in detection technology. Some additional details are given concerning plastic and liquid explosives.
- Tables of related European Commission funded research projects.
- A brief account of relevant European trade, safety and security legislation and a description of recent policy initiatives.

For the purposes of border security, checks are performed on passengers; carry-on luggage, checked baggage, vehicles and containers. Each detection technique is usually focused on either bulk explosives or traces of explosives. Detection of bulk explosives is carried out either by imaging characteristics of the explosive device or by detection of the explosive itself. Trace detection utilizes either emitted vapors from the explosive or explosive particles deposited on surfaces. Because of the wide range of energetic materials and the many differences in their physical properties, several detection devices detect only certain types of explosives and fail to detect others. In Appendix, table 8, physical and chemical properties of various common explosives are shown. In figure 23, the vapor pressure of common explosive materials is presented.

The nitro and nitrate component of some common explosives are the base of some detection methods, the nitrogen density of common materials and explosives are represented in Appendix, fig.22. Many detection devices readily detect conventional explosives made of organic nitro and nitrate compounds, but fail to detect explosives made of inorganic nitrates or non-nitrogenous compounds. In particular, many nitrogen-based detection devices fail to detect explosives such as ANFO (ammonium nitrate in fuel oil), and triacetone triperoxide (TATP). (Related characteristics of some plastic and liquids explosives are presented below in the description of the new threats).

The original vapor-based explosives detector is, of course, the dog, which is very effective for some purposes, but which has some serious "canine factor" limitations. Dogs, while very sensitive detectors, have limited attention spans, must be integrated as a team with a particular trainer to be most effective (thus generating high operating costs), and are often not consistent from day to day. They are still the best explosives detectors available for a wide variety of uses,

such as a sweep of a well-defined area in the wake of a bomb threat.

The methods and the equipment of explosive detection relating to the general use of the systems are presented in fig. 1 and fig. 2 below.

The methods may be categorized in several different ways, such as by context:

- Humans;
- Baggage;
- Vehicle;
- Containers.

Alternatively, they may be categorized by technique, as indicated in the figures 1 and 2.

General techniques of detection: (based mainly on source, [2], [4], [5] and [6]).

| **Trace detection Vapor/particle** | **Bulk explosives R&D methods** |
|---|---|
| Canine<br>Chemical<br>Optical<br>Biosensor | X-ray<br>Nuclear, Gamma ray<br>Electromagnetic<br>UV, Infra red, Radar<br>Terahertz |

Table 1: Categories of the general techniques of detection

| | Technology category | | Note |
|---|---|---|---|
| | Active | passive | |
| Bulk | X-ray<br>Gamma Ray<br>Acoustic<br>Fast/Thermal Neutron<br>UV, Infra red, Radar | | See table 9 for Company and Vendor |
| Trace | Reflection/ Photo acoustic Spectroscopy | Canine<br>Vapor/Trace Methods | See table 10 for Company and Vendor |
| R&D | Terahertz<br>Optical (non linear/ DIAL/DIRL) | Biosensor<br>Electronic nose<br>MEMS | |

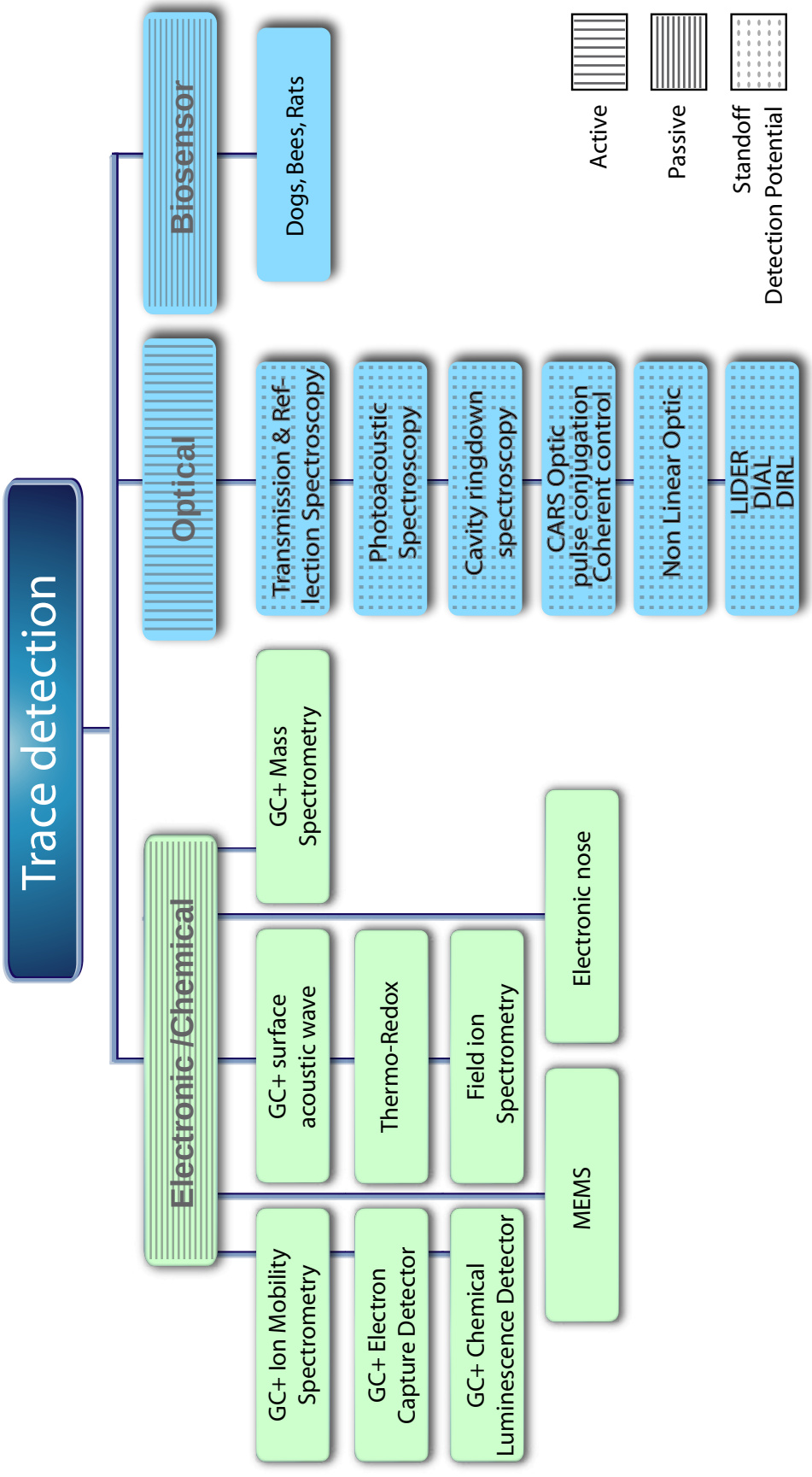
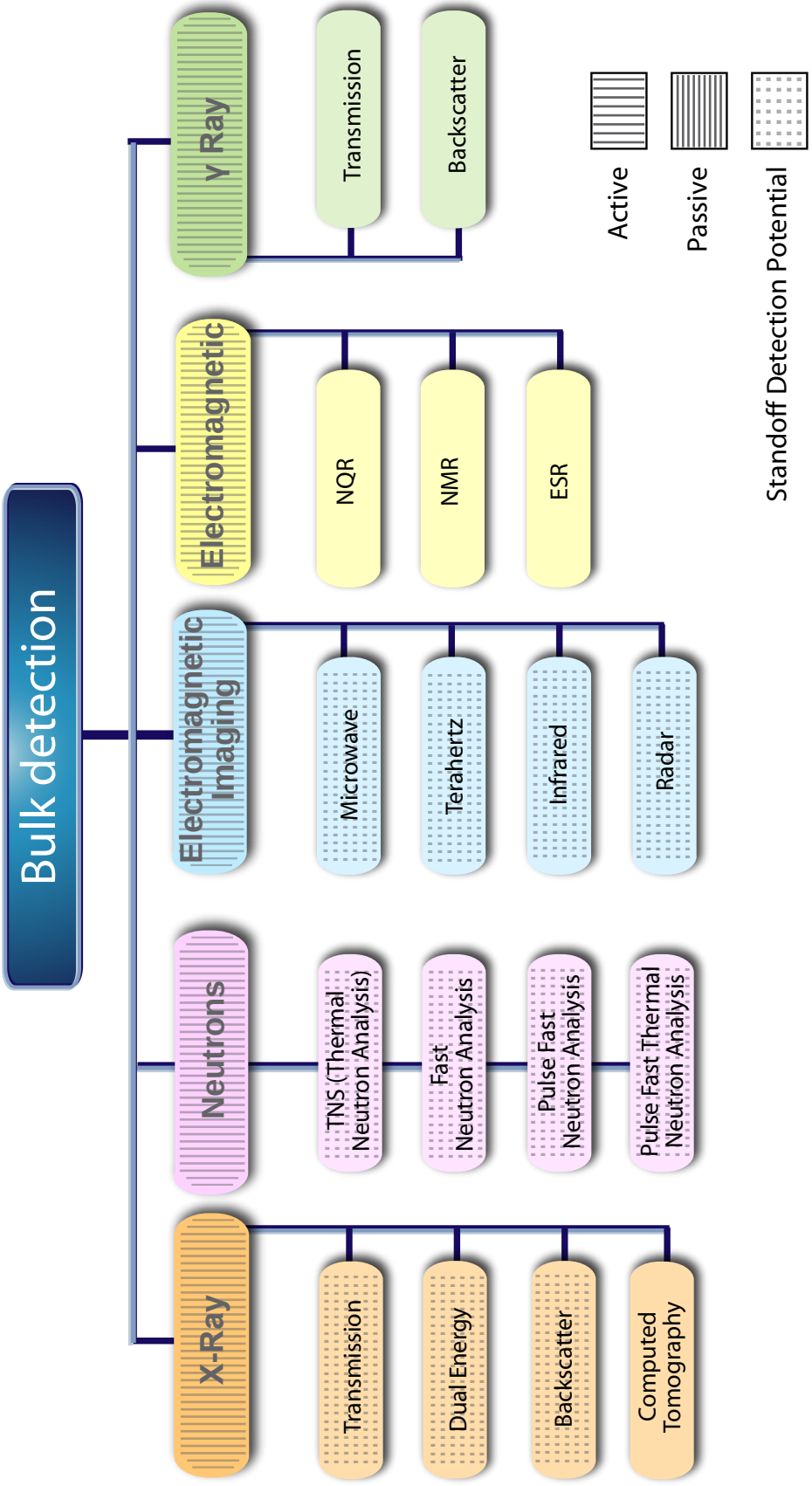



Figure 1: Explosive detection - Trace methods and equipment

Figure 2:
Bulk Methods
and equipment



# 2. Trace Detection Vapor/Particle Techniques

The term "trace detection" refers to detection of very small quantities of explosive, much smaller than those in the bomb itself, either in vapor and particulate form, defined in [6] as follows:

- **Vapor** — Gas-phase molecules that are emitted from a solid or liquid explosive. The concentration of explosives in the air is related to the vapor pressure of the explosives material and to other factors such as the amount of time the explosives material is present in a location, its packaging, air circulation in the location, etc.
- **Particulate** — Microscopic particles of the solid explosives material that adhere to surfaces (i.e., by direct contact with the explosive, or indirectly, through contact with someone's hands who has been handling explosives).

## 2.1 Trace Detection Basic Operations

Trace explosive detection systems always perform three operations: sampling, selection and detection. Sampling is the collection of material from the object or region under investigation and its transport to the instrument. Selection is the separation of substances in the sample which could be explosive from those which could not be. Detection is the measurement of how many molecules have passed the selection process. In general, these operations may be combined together or separated into different process steps.

Performance limits exist on all three operations which lead either to some explosive molecules not being counted or to non-explosive molecules being mistakenly counted. If one wishes to ensure that no explosive molecules are missed, the price to pay is that some non-explosive molecules are included i.e. there is a trade-off between selectivity and sensitivity. The instrument designer has some discretion over where the balance is struck.

The word "detector" is sometime used to denote just the sensor used for the detection of the selected molecules and sometimes the overall system. It is important to make clear in context which one is referring to.

The most difficult challenge of trace explosives detection is that of sample collection and transport to the instrument. Particulate sampling usually requires direct contact to remove material from a contaminated surface. Vapor sampling requires no contact but is made difficult by the very low vapor pressures of common organic-based explosives such as TNT, RDX, and PETN (especially the last two) and by the presence of polymeric binders, plasticizers and/or waxes. Fig. 23 in Appendix shows values. Confinement and packaging of the explosive may be assumed to further reduce the vapor concentration by one order of magnitude in a practical detection scenario. For both trace methods, another important difficulty is cross-contamination of samples, because explosive molecules are highly adsorptive and will adhere or stick to nearly all surfaces.

On the other hand, this property can also be used to advantage to concentrate

explosive material from a large sample. Special matrix materials and coating may be used to enhance this process of selective adsorption.

Some explosive detection systems incorporate a pyrolization step: the sample trace or vapor is heated strongly enough to decompose it into simple gas molecules, for example nitrogen oxides. The detection stage is made to be sensitive to these. In this case, the detector will respond to any substance which decomposes to these gases on pyrolization. So it is an operation which tends to increase sensitivity and decrease selectivity.

We describe here the techniques in approximate order of technology readiness, beginning with those routinely in use and ending with those still in the research phase.

## 2.2 Techniques

### 2.2.1 Ion mobility spectrometry

Ion mobility spectrometry (IMS) is the most common technique used in commercial instruments for trace explosives detection. The attractive features of high speed, comparatively low cost, high convenience, strong reliability and sound performance of IMS have favored applications in many explosives detection scenarios. IMS instruments can operate in particulate and/or vapor modes. Instrument formats range from small, hand-held devices to large, dedicated-site portal systems.

IMS detection separates ions by how quickly they drift through a gas. Fig.3 shows a typical layout. The sample is delivered to the ionization region of the instrument, where negative ions are formed by irradiation. These ions are accelerated by an electric field and admitted via a shutter into the drift region, which is usually tube-shaped and at atmospheric pressure. Focusing electrodes keep the ion beam from spreading laterally. As the ions exit from the drift region, they are counted, usually by a simple Faraday cup, i.e. the ions collide with a metal plate and deposit their charge, which is counted electronically. The time required from the moment when the shutter is opened until the ions are registered by the counter is called the drift time and is a complex function of the charge, mass, and size of the ion, characteristic for each species. Materials are identified as possible explosives if their drift time corresponds to that of known explosives.

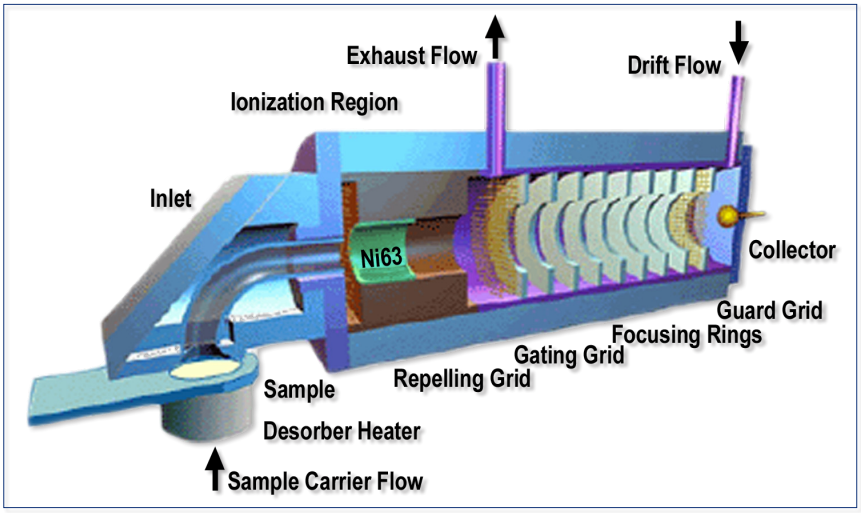



Figure 3: Schematic view of IMS principle [21]

Ion mobility spectrometry is thus based upon two principles: (1) the ionization of sample molecules through gas phase chemical reactions by the transfer of an electron or a proton, and (2) the characterization of these ions based upon gas phase mobility in a weak electric field. The mass, size, and shape of these ions will govern the mobility through a voltage gradient, and this can be measured as time required to traverse a fixed distance. Thus IMS detectors yield a drift time or mobility value which is characteristic of certain ions (i.e., chemicals) and provide specificity of response.


Figure 4:
Examples of fielded IMS Equipment (Photo furnished by Smiths Detection)

Some instruments have been made which use chemical ionization e.g. with methylene chloride but radioactive ionization with Ni63 is usually preferred as being simpler and more effective and because the source required is weak enough not to present an excessive safety hazard or regulatory burden.

The drift time is sensitive to pressure and so changes with weather conditions and altitude. Little more than routine, periodic recalibration is needed to cope with this, but users do need to be aware of the issue.

A drawback of IMS technology is poor peak resolution in mixtures, which real-world samples invariably are. Two different materials that form ions of similar size and mass may give similar drift times and appear as a single broad peak rather than two distinct peaks in an IMS spectrum. To resolve the overlapping peak problem it is necessary to separate the molecules on the basis of some other property i.e. to provide an additional selection process.

### 2.2.2 Mass spectrometry (MS) (GC/MS)

Mass spectrometry (MS) is a selection method based on the charge and mass of ions. MS systems consist of an ionization stage followed by arrangement of electrodes and/or coils for generating an electromagnetic field designed such that ions with different charge to mass ratios will either follow different trajectories through it and exit at different places or have different times of flight. The final stage is a counter, which can be a Faraday cup but is usually an electron multiplier, a more sensitive device employing the avalanche effect.

In contrast to IMS, in MS the separation process occurs in high vacuum. The oldest form of MS, called sector MS, uses an accelerating d.c. electric field followed by a d.c. magnetic field which bends the ions' trajectories through the sector of a circle, with radius dependent on the charge to mass ratio. Modern systems may use other arrangements, including r.f. fields as in, for example, the quadrupole MS, in which there are four parallel cylindrical r.f. electrodes arranged in a square.

For a given ion, the charge is an integer and the mass, at least for stable ions, is defined to several significant figures, so the charge to mass ratio is a precise characteristic. Typically, as well as ionized whole molecules, ionic fragments are also found, giving a spectrum characteristic of the substance. With careful instrument design, the MS peaks of stable ions can be made very narrow, making MS a much more discriminating form of separation than IMS. The engineering required, however, is significantly more demanding.

### 2.2.3 Gas chromatography

Gas chromatography (GC) is a selection technique based on the degree to which gas molecules are adsorbed by a solid. The sample is introduced into a gas chromatographic column, which is a narrow tube coated internally with a material which binds more strongly with some substances than with others. The sample molecules in the column are partitioned in dynamic equilibrium between a mobile phase flowing down the column and a stationary phase adsorbed onto the coated walls. Substances which are adsorbed more strongly travel down the tube more slowly, so the GC resolves a mixture into its components. A suitable detector is placed at the end of the column. The time required for each chemical substance to travel the length of the GC column, called the retention time, is determined by the equilibrium constant. The detector in a GC system can be chosen to be selectively sensitive to species of interest, examples used in explosives detection are given below. A more sophisticated method is to use the GC to separate a sample prior to introduction into an IMS or MS.

To improve upon the IMS trace detection systems currently used, MS is an obvious candidate to consider. Most of the currently available GC/MS are laboratory systems but portable ones are becoming available. Their weight is around 30kg and their throughput about 3 samples per hour. Portable units need about 5 min. but need warm up time of 45 mins. They should really be considered substance identifiers rather than trace detectors. The cost is 135-215 k$. There needs to be more R&D effort to make this method achieve low cost and reasonable throughput.

Figure 5: Portable commercial GC/MS explosives detection systems (photos furnished by: Constellation Technology Corporation (left) and Bruker Daltonics (right))

## 2.2.4 CHEMILUMINESCENCE (CL)

Chemiluminescence is the production and emission of light that occurs as a product of a chemical reaction(s) according to the scheme

A + B —> products + light

Most common explosives materials contain nitrogen (N) in the form of either nitro ($NO_2$) or nitrate ($NO_3$) groups. Additionally, most explosive material taggants used in plastic explosives also contain $NO_2$ groups. The most commonly used chemiluminescence reaction scheme for explosives detection involves infrared radiation (IR) light emission from excited-state nitrogen compounds. The produced IR light is directly proportional to the amount of NO present, which is related to the amount of the original nitrogen-containing explosive material that was present.

**CL discussion**

One common CL technique is to pyrolyze the vapor from the sample and react with ozone. If nitro groups are present, then a reaction between the ozone and nitric oxide NO takes place which produces an excited, metastable state of nitrogen dioxide $NO_2$*. On return to its ground state $NO_2$, it emits near-infrared light of 1200nm wavelength, which can be detected with a photodiode or other suitable semiconductor sensor. Since nitrogen-containing molecules found in fertilizers, some perfumes and other common materials may cause the same reaction, chemiluminscent detectors typically are not used alone but are fitted with a front-end chromatograph column (GC). The combined GC/CL provides a unique GC retention time and separates materials prior to their CL detection.


Figure 6: Chemiluminescence explosive detection systems *(Photo furnished by Scintrex Trace Corporation and by Thermo Electron Corporation)*

A significant weakness of $O_3$/NO reaction detectors is their inability to detect explosives that are not nitro-based. The Scintrex EVD 3500 (Fig. 6, top) employs an alternative chemiluminescent detection technique, reaction with luminol, a chemical which photoluminesces in the present of certain oxidizers. This method reveals peroxide-based explosives as well as nitro-based.

## 2.2.5 ELECTRON CAPTURE DETECTOR

The electron capture detector (ECD) is a counter suitable for good electron acceptors, such as are present in many explosives. 63Ni is a radioactive isotope which emits electrons. As the sample passes over the 63Ni, it will pick up these “loose” electrons if it has an electronegative functional group, The detector sees the loss of electrons (a loss of current), and interprets it as a peak. This detector is

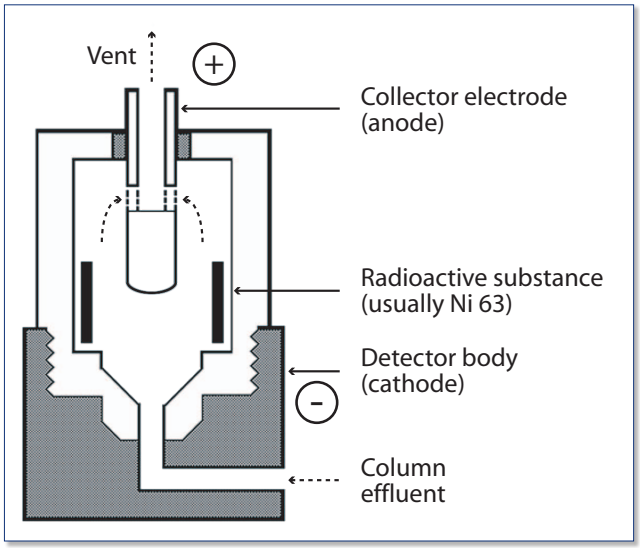



Figure 7: Electron capture detector principle [27].

very sensitive to halogenated compounds, as well as compounds with very electronegative functional groups such as nitro groups and peroxides. The detection limit of this detector for halogenated compounds can be as low as the picograms level. This detector cannot detect compounds such as hydrocarbons, amines, and alcohols.

An example of a current MS development system is described in [4]. Nine nitrogen-containing explosives (EGDN, DMDB, NG, PETN, RDX, HMX, NT, DNT, and TNT) can be confirmed at subnanomole amounts using methylene chloride chemical ionization and detection of negative ions. (This is nearly the same ion source chemistry as is used in IMS, for those versions which do not use a radioactive source.) The time for analysis was less than 10 minutes.

## 2.2.6 Electrochemical Detectors and Thermo-Redox

The electron accepting properties of nitro groups are also the basis of electrochemical detectors. The sample is introduced into a cell with electrodes made from different materials which are chosen so that an electron-accepting substance will draw electrons preferentially from one, the cathode, causing a voltage change between it and the other, the anode. A reference electrode may also be used.


Figure 8: Hand-held commercial thermo-redox explosives detection system from Scintrex Trace Corporation, EVD-3000

Thermo-redox (Figure 8) is a proprietary technique incorporating selective adsorption, pyrolization and electrochemical detection.

## 2.2.7 Surface Acoustic Wave Detector

Surface acoustic wave (SAW) devices are piezo-electric crystals with characteristic acoustic resonant frequencies. They can be used as chemical detectors because, when molecules from a sample are adsorbed onto the crystal surface, the resonant frequency is changed. Adsorption is usually greater at lower temperatures so, in each detection cycle the crystal is first heated to purge it and then cooled to arm it for detection. SAW detectors will respond to any molecule which is adsorbed onto the surface, they are not inherently selective. For explosive detection, they are usually employed with a GC front-end but selectivity can also be introduced by a special coating.


Figure 9: Portable commercial GC/SAW explosives detection system from Electronic Sensor Technology (*Photo furnished by Electronic Sensor Technology*)

## 2.2.8 Research in Ultra-violet (UV) fluores-cence

UV fluorescence is a technique currently under development in which trace amounts of explosives materials fluoresce when UV light illuminates the explosives material. A portable trace explosives detection system based on UV fluorescence released by CDEX Inc. has been developed called the Personal Security Screening System (PS3). The PS3 is designed for handheld scanning of people and their personal effects, using a wand connected via fiber optic cables to a UV source and detector, to identify presence of trace explosives (e.g., RDX, C4, Semtex, TATP, and TNT) and other substances on surfaces impacted by the UV energy. Target areas are scanned to detect explosives, and to detect drugs such as Cocaine and Heroin. The output of visual and audible alerts requires no operator interpretation of positive or negative indications. The rechargeable batteries would have an operating time of four to six hours, and be capable of easy replacement while in the field. Such equipment is the forerunner technology for a mobile personnel portal for rapid screening of individuals.

## 2.2.9 Research in Micromachined Cantilevers

A promising technology under investigation today is in the area of micromachined cantilevers. Tiny micro cantilevers are coated with polymers that can adsorb various chemicals. As the chemicals are collected the microcantilever's mass properties change and these changes are detected with optical and electrical measurements. The importance of this technology is that it provides sensitivity much greater than that of sniffing dogs and can detect a wide range of organic and inorganic chemicals.

## 2.2.10 Research in Optically-based methods for vapor detection

Only a few classes of explosives have sufficient vapor pressure to permit detection of gas clouds from afar. Instead, most are detected from trace samples obtained by swabbing the suspected area, followed by mass-spectrographic or gas-chromatographic detection.

The stand-off detection of explosives is being pursued. Some of the more promising techniques include work on remote Raman LIDAR (light detection and ranging, the visible-band analogue of radar) for detection of RDX explosive samples, remote LIBS (laser-induced breakdown spectroscopy) for detection of TNT solid samples, DIAL sensing (differential absorption LIDAR) of selected explosive vapors, and CARS (coherent anti-Stokes Raman spectroscopy) detection of remote samples.
In some of these cases, new types of lasers (such as room temperature tunable quantum cascade lasers and mid-IR pulsed lasers) will greatly enhance the detection capability. Most of these techniques are being developed as part of a larger combined effort using sensor fusion.

Other research is being pursued to detect chemicals related to the manufacturing of the explosive.

Also, millimeter radar imaging can, in some cases, detect hidden packages under clothes when coupled with video tracking, but further testing is required to determine the overall false alarm rate and utility.

## 2.2.11 Canine Stimulants and Training Aids

Non-explosive canine training aids have been developed and field-tested at several major airports. Previously, actual explosives were required to perform maintenance training of canines in the field. This caused difficulties with the transport and storage of the explosives and reduced the frequency of training.

This project demonstrated that the use of non-explosive odor replicates does not diminish a canine's ability to detect explosives. These training aids provide a means to augment existing canine training scenarios where the use of real explosives is impractical.

### 2.2.12 Biochemical methods

Immunological and enzyme detection methods offer the possibility of excellent sensitivity and selectivity [1], [24]. It is possible to make antibodies which are specific to TNT or other explosive molecules which, for example, can be bound onto the substrate of a micromechanical sensor, such as a cantilever. Antibodies leave the substrate in the presence of the explosive, changing its resonant frequency [25]. Enzymes which participate in bioluminescent or color changing reactions can be modified to react with or bind to explosive molecules in such a way that the presence of the explosive causes a visible change. This type of reaction may be used as the basis of electronic biosensors or test papers or fluids. Enzyme linked immunosorbent assay (ELISA) is a hybrid technique which uses a visible change from an enzyme reaction to detect the concentration of specific antibodies. In ELISA, both the antibodies and the enzyme conjugate are made specific to the molecule to be detected.

# 3. Bulk explosive detection techniques

Bulk explosive detection systems are designed to detect macroscopic masses of explosive, large enough to be visible to the eye, by means of their interaction with some form of penetrating field or radiation. The explosive material is distinguished from its surroundings by its absorption, backscatter, fluorescence, resonance etc. Most bulk detection systems aim to reveal chemical characteristics, such as the atomic number of the elements present, which may not be unique to explosives but provide a strong indication of their presence. Bulk detection instruments often produce images of the inspected item, a suspect bomb being revealed by its shape, as well as its chemistry.

The commercially available bulk detection techniques include the following:

- X-Ray
- Gamma-Ray
- Non-ionizing electromagnetic
- Neutron

The same trade-off between false alarms and false negatives applies as with trace detection systems: to be sure to keep the probability of false negatives acceptably small, some false alarms must be tolerated. Good statistical performance has traditionally depended on well-trained operators, although the image-quality of modern systems can be good enough to allow automatic screening e.g. of luggage.

## 3.1 X-ray and gamma ray techniques

Gamma rays and X rays, like microwaves and visible light, are part of the electromagnetic spectrum. X rays are high-energy radiation and are slightly lower in energy than gamma rays and they differ in their origin. Gamma rays originate in an atom's nucleus, and are produced by radioactivity. X rays originate outside an atom's nucleus in the area where the electrons reside. Both gamma rays and X rays pose safety hazards.

When X rays and gamma rays encounter matter, three outcomes are possible. They may

- pass through the material (transmission),
- be absorbed (absorption), or
- be deflected off of its original course (scattered or backscattered.)

The main parameter that determination the outcome: energy use and bulk characteristic as: density, absorption coefficient, backscatter coefficient, and Z number.

The main X-ray technologies currently available:

- Single energy
- Dual energy
- Computed tomography (CT)
- Backscatter (including a personnel screening technique)
- Fluoroscopy

## 3.1.1 Single energy


Figure 10: Commercially available single-energy X-ray baggage and parcel inspection system (Photo furnished by Rapiscan Systems who also manufacture dual-energy instruments.).

Single-energy imagers are the simplest kind of X-ray system. Strictly speaking, they are not explosive detection systems because the image just shows the degree of absorption of the X-rays, which is not specific to explosives, but they can reveal the presence of explosive devices by showing fuzes, wires etc.

Although today regarded as less than state-of-the-art, they can still be a valid, low-cost security measure in contexts where more elaborate solutions would not be justified.

Cargo and vehicle screening systems which require a very high-energy X-ray beam to penetrate metal panels are often single-energy.

## 3.1.2 Dual energy

The two basic types of dual-energy systems utilize: a single broadband X ray beam and a dual detector arrangement, or separate low-energy X-ray and high-energy X ray beams.

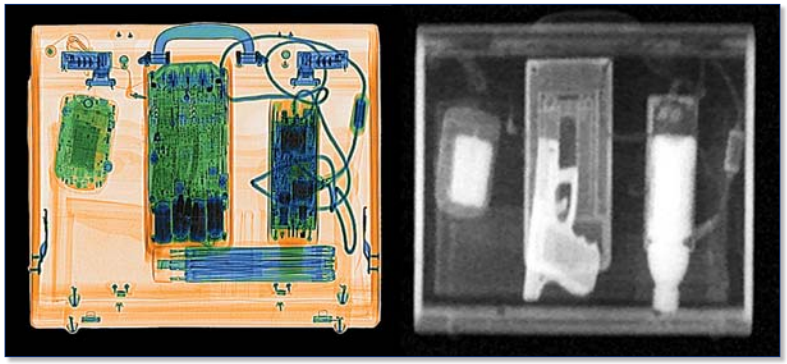
X-ray data are obtained at both X ray energies. The two independent images are computer-processed to compare low-energy to high-energy X ray absorption. The displayed results characterize and identify the various materials by their shape, and artificial colors are assigned to different Z-numbered materials. The system uses color to separate items in the image into organic (low Z number) and inorganic materials (high Z number.) The resulting image is displayed on a monitor for visual identification.


Figure 11: Commercially available dual-energy system & image, with the area of concern, marked with a red frame (Photo furnished by L3 Communications, Security and Detection Systems)

## 3.1.3 Backscatter

Systems produce an image from X-rays that are scattered back from the screened object towards the source (not only transmitted as in the standard machines described above). Because low-Z materials are more efficient at scattering X-rays, explosive-like materials are more contrasted – they stand out clearly – in the backscatter image, while they often are barely visible in the transmitted image (low contrast). The backscatter image is indeed usually most effective for the detection of low-Z materials such as explosives, while the transmission image is most useful for viewing metals. Backscatter systems can display both the backscatter and transmission images. Quantitatively, a measure of the backscattered X-rays together with the standard absorption measurement provides information which can help in separating the effects of density and effective atomic number $Z_{eff}$, in order to identify high density, low $Z_{eff}$ materials (the signature of explosives).

X-ray fluorescence is a more sophisticated form of backscatter in which the elements present are recognized by their emission of secondary X-rays at characteristic frequencies [26].



Transmission Backscatter

Figure 12: Dual energy image of a briefcase on left shows a PDA and laptop power cord. The backscatter image of the same briefcase on the right shows that it also contains a Glock handgun and plastic and liquid explosives. (Photo furnished by A S & E)

## 3.1.4 Computed Tomography (CT)

CT is an even more sophisticated X-ray technique in which cross-sectional images ("slices") through an object are numerically reconstructed from X-ray projections at various angles around the object. These cross-sectional images can be added together to produce a three dimensional image (as in medical CAT scans). Along with the three-dimensional image, the effective Z number is calculated and materials with the same Z number as explosives can be identified.

Discussion of X-ray systems [6]
Advantages of dual-energy X-ray systems are:
material discrimination based on shape, the ability to detect metals and other high Z number materials in addition to explosives, low cost systems are available.

The disadvantages of dual-energy X-ray systems are: it can be difficult to separate objects from one another in an image, especially when the object does not strongly interact with X-rays; the dual-energy technique does not determine a material's thickness, therefore, it cannot unambiguously determine the Z number of a material.

Figure 13: Commercial CT system (photo furnished by InVision technologies)

Low cost baggage screening system costs start at only $25,000 and automated baggage screening systems cost up to $300,000. Cargo screening system costs vary greatly depending on X-ray strength and penetration, but systems cost from $60,000 to $900,000

Some low energy X-ray backscatter systems exist for screening people and finding explosives, arms and contraband hidden on their bodies, for example those made by A. S. & E. and Rapiscan. The technology must achieve adequate image quality at a radiation level low enough to comply with statutory or recommended exposure limits. Fig. 14 shows an image from the A. S. & E. SmartCheck system, which is stated by the manufacturer to give a dose of less than 0.1μSv per scan, well within National Council on Radiation Protection and Measurements and ANSI recommendations, even for frequent travellers, pregnant women and children. The scan has to be made twice, front and back, in order to be sure that there are no hidden objects on the body, because the radiation goes through clothing but not right through the human body like a medical X-ray. The images in Fig. 15 show a subject's body in outline form, to avoid the privacy objection to displaying a nude figure.

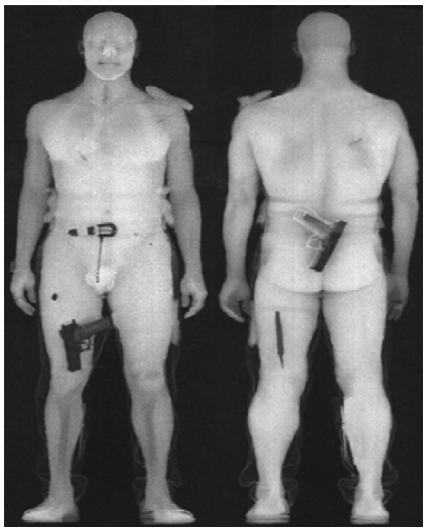


Figure 14: Low-dose backscatter X-ray image of a fully clothed man displays hidden organic and inorganic materials (Photo furnished by AS&E)

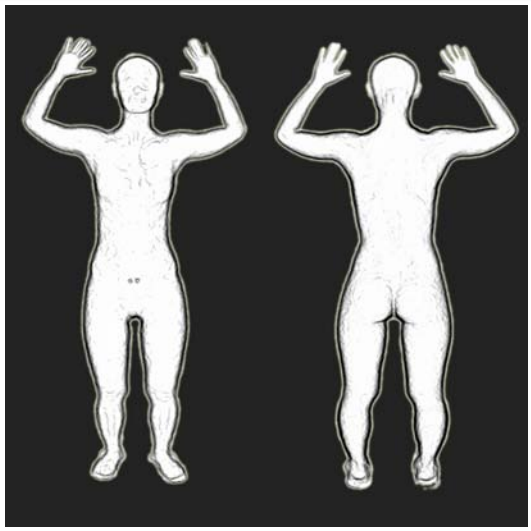


Figure 15: Silhouette presentation for enhanced privacy (Photo furnished by AS&E)

## 3.15 X-RAY DIFFRACTION (XRD) AND X-RAY DIFFRACTION IMAGING (XDI)

X-rays passing through a material are scattered from each atom. In a crystal, atoms are arranged in a repeating pattern called a lattice. Scattering of X-rays from many atoms at equivalent positions in the lattice causes the formation of a pattern of dots called a Laue pattern from which it is possible to infer information about the structure of the lattice and the spacing between the atoms.

When XRD is applied for security purposes [3], the object to be inspected is not a pure crystal, so the diffraction pattern is blurred into a continuous function of angle. Typically, the sample is irradiated with a range of energies and a plot is made of scattered intensity as a function of momentum transfer, at fixed scattering angle. The curves obtained are characteristic of particular substances. Higher energy X-rays are needed to penetrate the object than are used in classical XRD, e.g. 150keV. Remarkably, the technique can to some extent work even for liquids.

X-ray diffraction imaging (XRI) is the most advanced form of XRD. Directly by collimation and/or indirectly by computerized tomography, the X-ray beam is

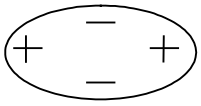
focused on a limited region of the object, enabling a spatial map of the scattering curve to be produced. In its most general form the image is 4-dimensional, with three spatial coordinates and a momentum transfer coordinate.

## 3.2 Non-ionizing electromagnetic field based methods

A number of techniques are available for detection of explosives which employ much lower frequency electromagnetic fields which have resonances with atoms found in the material which it is required to detect, but which are incapable of ionizing atoms. This type of field does not present the same safety hazard as ionizing radiation, such as X rays and gamma rays.

### 3.2.1 Nuclear quadrupole resonance

Nuclear quadrupole resonance (NQR) is an explosives detection method based on detection of the nitrogen 14 nucleus by means of its electric quadrupole moment i.e. a distribution of electric charge with negative charge nearer the centre of the nucleus and positive charge towards the sides;



The $^{14}N$ nucleus has a relatively large quadrupole, making it suitable for detection by this method. Each nitrogen atom acquires a small additional energy as a result of its quadrupole aligning with local gradients in electric field in the molecule. When quadrupole nuclei are exposed to a pulsed radio frequency (RF) field at the resonant frequency, they move to a higher energy state. Upon removal of the RF field, the nuclei return to their original lower energy state, the excess energy is released and a weak RF return signal may be detected. The $^{14}N$ nucleus also possesses a magnetic dipole so that the ensemble of nuclei may be excited, and changes detected, by means of a simple coil antenna.

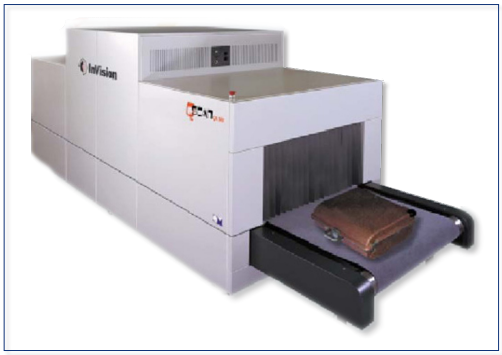


Figure 16: Nuclear quadrupole resonance luggage inspection system (Photo furnished by GE Security)

Discussion of NQR

The internal electric field gradients are a characteristic of the material, and hence each material has characteristic resonance frequencies, so NQR can be used to detect different chemical species. The released energy, and the frequency of the resonance, is characteristic not only of the isotope and the chemical formula but also the molecular and crystal structures. NQR is sometimes referred to simply as quadrupole resonance (QR). NQR advantages are: no ionizing radiation source is used, it is highly specific for the identification of explosive compounds, there is little interference from other nitrogen-containing materials that may also be present, it has very low false alarm rate and the probability of detection for a given explosive mass is shape independent for NQR. Disadvantages of NQR include the following: it is susceptible to shielding (notably metal shielding.) Not all types of explosives can be detected, only those that contain nitrogen. It requires proximity of the object to the RF field source. Thus, the primary application of this technology has been the screening of relatively small items such as mail, small packages, and baggage. Because metal shielding can make an explosive invisible to NQR, this technique needs to be used in combination with another complementary technique.

## 3.2.2 Nuclear magnetic resonance

Nuclear magnetic resonance (NMR) is a technique that has not yet been widely utilized in the detection of explosives but is very well-known for other applications. NMR is similar to NQR except that in NMR the energy level splitting is due to an externally applied magnetic field, which interacts with the magnetic dipole of the nucleus. In NMR the resonant frequency is defined mainly by the isotope and the strength of the applied field but there is a subtle shift caused by the molecular environment i.e. the material's chemistry. This contrasts with NQR, where the resonant frequencies can be completely different for the same isotope in different materials.

Pulsed NMR to examine H-N coupling via T1/T2 measurements.
Two parameters have a particular importance, T1 and T2. T1 is the so-called spin-lattice relaxation time, which is the characteristic time for a nuclear spin system to come to equilibrium with its surroundings after a disturbance (such as the previously mentioned RF pulses, or a change in the applied field). T1 sets the time required to detect an NMR response, and the rate at which NMR tests might be repeated without signal degradation. T2 is the so-called spin-spin relaxation time, which is the characteristic time for a spin system to come to transversal equilibrium following a disturbance i.e. for the distribution of spin-components orthogonal to the applied magnetic field to reach thermal equilibrium. The transient, free induction decay (FID) signal following a single transmitter pulse decreases in amplitude at a rate which is dependent upon T2 (in a homogenous magnetic field). T1 and T2 are characteristic of the molecular structure and the state of the sample material. Measurements have been reported, in particular at a frequency of 3 MHz, showing that these two constants for explosives are well-separated from those for other common materials of interest, T1 being long (1-10 sec) and T2 short ($10^{-4}$- $10^{-6}$ sec)

Comparison of NMR and NQR
The requirement of a strong homogeneous auxiliary magnetic field is a disadvantage by comparison with NQR. Even though the resonance frequencies in NQR are low and hence the technique is a less sensitive technique than NMR, nonetheless, NQR has been demonstrated to be useful in practice for explosives detection. While NMR in the laboratory using different atoms is an excellent analytical technique, in practice for finding explosives in the field it is the hydrogen NMR signal that is obtained. The hydrogen in most explosives exhibits very long T1 and very short T2 NMR relaxation times, and so the explosive can be distinguished from most other benign materials. These magnetic resonance techniques require close proximity (<1 m) to a large amount (>10 g) of bulk explosive. This limit makes magnetic resonance techniques ill suited to standoff detection.

## 3.2.3 EPR – ESR

Electron Paramagnetic Resonance (EPR), often called Electron Spin Resonance (ESR), is similar to (NMR) but works with the electron spins rather than the nuclear spins. Electromagnetic radiation (usually of microwave frequency) is absorbed by molecules, ions, or atoms possessing electrons with unpaired spins,
i.e. electronic spin S > 0.

## 3.2.4 Terahertz

Electromagnetic radiation at certain frequencies of the order of terahertz ($10^{15}$Hz) is less attenuated by the atmosphere than frequencies a little higher or lower: transmission "windows" are said to exist in the terahertz band, making it attractive for stand-off detection systems. An example of recent research in this field is given in [17]. Portable standoff imaging system definition was carried out, and a

comparison of general imaging system performance for several basic imaging system designs was completed and detailed, tabulated analysis of standoff imaging system performance was carried for a system based on the ultra-sensitive heterodyne detection technique, wherein both the transmitter and the local oscillator in the receiver utilize terahertz quantum cascade lasers. Such lasers have demonstrated power levels adequate for the proposed system. This standoff detection system appears to be the most promising for detection of hidden weapons and explosives on individuals at standoff distances.

Measurements of terahertz radiation over the 0.3 – 4.0 THz spectral range were carried out at sea-level for RH values ranging from 5 % to 58 %.

Five transmission windows occurred in the spectral regions between 3.39 – 3.47 THz, 2.51 – 2.55 THz, 2.09 – 2.12 THz, 1.96 – 2.0 THz, and 1.47 – 1.56 THz.

The 1.5 THz design, which involved a 1 cm x 1 cm target imaging resolution (pixel size) at a target distance of 50 m, does not provide adequate system sensitivity at normal atmospheric humidity levels. Since moderate to high atmospheric humidity levels must realistically be dealt with, two possible tradeoffs were investigated. Reducing either imaging resolution or operational target distance results in improved system sensitivity. A reduction in imaging resolution from 1 cm x 1 cm to 10 cm x 10 cm, results in acceptable sensitivity at 50 m target distances, whereas maintaining the 1 cm x 1 cm image resolution results in the achievement of adequate sensitivity at distances of about 10 m. Intermediate target resolution/ target distance combinations could also provide adequate system sensitivity.

### 3.2.5 Man Portable Passive Millimeter Wave

Prototype standoff personnel screening system are being developed based on passive millimeter wave technology. This technology is an adaptation of prior development work in the area of obstacle avoidance. Imaging capabilities will be enhanced to resolve threat objects concealed beneath clothes at a specified standoff distance.

Some will use focal plane imaging and will operate in frequencies of 80-100 GHz passive, which provides good clothing penetration with a reasonable size for resolution and standoff. A demonstration system by Lockheed Martin [18] has been operated at 5m standoff. Pharad Inc. have built a system using wideband MMW signals in the Ka- band (26-40 GHz) to excite natural resonances in concealed weapons. A sensor module transmits a wideband MMW signal and excites the natural resonances of the selected target. A MMW receiver senses the scattered radiation due to the natural resonances and extracts the signature of the weapon and compares it to a set of database.

## 3.3 Neutron-based technologies

Systems based on neutron physics and neutron-excited gamma spectroscopy use penetrating neutron radiation which interacts with certain nuclei in such a way as to give the possibility of determining the elemental densities or elemental ratios of those elements. These include several important light elements, such as carbon, oxygen and nitrogen.

Explosives have unique nuclear signatures as shown in Table 2 and ref. [14] and [11]. (The same basic reactions are also of interest for detection or identification of narcotics [11] ).

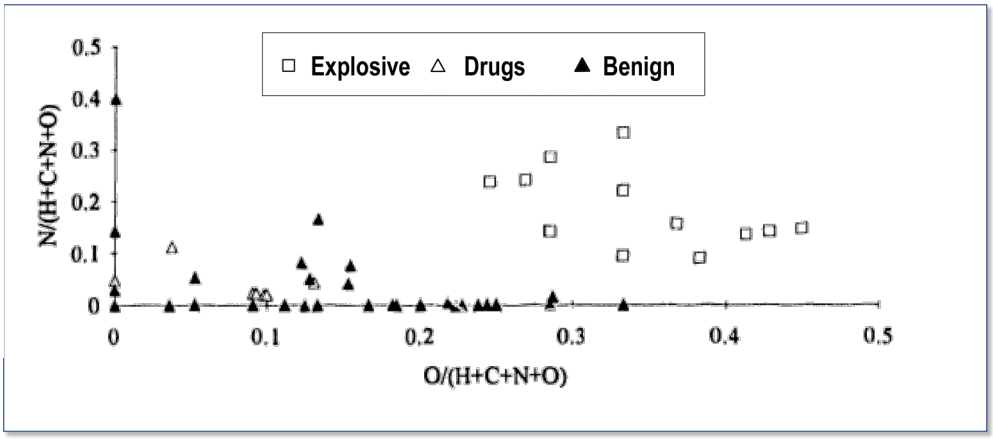



Figure 17: Two-dimensional representation of elemental compositions of explosives, drugs, and benign substances in terms of the normalized number densities of oxygen nitrogen [11]

Table 2: Nuclear reactions of interest for the detection/identification of explosives [14]

| Element | Reactions | Neutron Energy | Reaction Type |
|---|---|---|---|
| H | $^{1}H(n,\gamma)^{2}H$ | Thermal | Prompt |
| C | $^{12}C(n,n'\gamma)^{12}C$ | Fast(>5MeV) | Prompt |
| N | $^{14}N(n,\gamma)\ ^{15}N$ | Thermal | Prompt |
| N | $^{14}N(n,n'\gamma)^{14}N$ | Fast(>3MeV) | Prompt |
| N | $^{14}N(n,2n)^{13}N$ | Fast(>14MeV) | Activation (9.9min) |
| O | $^{16}O(n, n'\gamma)^{16}O$ | Fast(>7MeV) | Prompt |
| O | $^{16}O(n,p)^{16}N$ | Fast(>9MeV) | Activation (7.13s) |
| Cl | $^{35}Cl(n, \gamma)^{36}Cl$ | Thermal | Prompt |
| Cl | $^{35}Cl(n, n'\gamma)^{35}Cl$ | Fast(>3MeV) | Prompt |
| Cl | $^{37}Cl(n,p)^{37}S$ | Fast(>14MeV) | Activation (4.9min) |

Table 3: Elemental densities and ratios of three classes of substances. [15]

| Density or Ratio | H | C | N | O | Cl | C/O | C/N | Cl/O |
|---|---|---|---|---|---|---|---|---|
| Narcotics | High | High | Low | Low | Medium | High, >3 | High | Very High |
| Explosives | Low-Medium | Med | High | Very High | Medium to None | Low, <1 | Low, <1 | Low to Medium |
| Plastics | Medium-High | High | High to Low | Medium | Medium to None | Medium | Very High | - |

Neutron scanning technologies include several methods, distinguished by the source and the neutron energy used for detection:

a) Thermal Neutron Analysis (TNA)
b) Fast Neutron Analysis (FNA)
c) Pulsed Fast Neutron Analysis (PFNA)
d) Pulsed Fast Thermal Neutron Analysis (PFTNA)

In these technologies, the neutrons create gamma-ray signals when they interact with the elemental ingredients of the inspected object. The gamma-ray energies are unique to the elements in the inspected object. If the gamma-ray signatures match those in a threat database, the system automatically alarms.

PFNA can generate three-dimensional, characteristic gamma-ray maps and is able to detect explosives and drugs hidden in vehicles and in large cargo containers. However, it also has a number of practical limitations, including large size and weight, the need for radiation shielding, difficulty in penetrating hydrogenous materials, and regulatory and safety issues associated with nuclear-based technologies.

The neutrons used in a thermal neutron activation system are provided by either a radioactive isotope or by an electronic neutron generator. An electronic neutron generator adds cost and experimental complexity to the system, but it has a safety advantage over a radioactive source in that the stream of neutrons can be turned

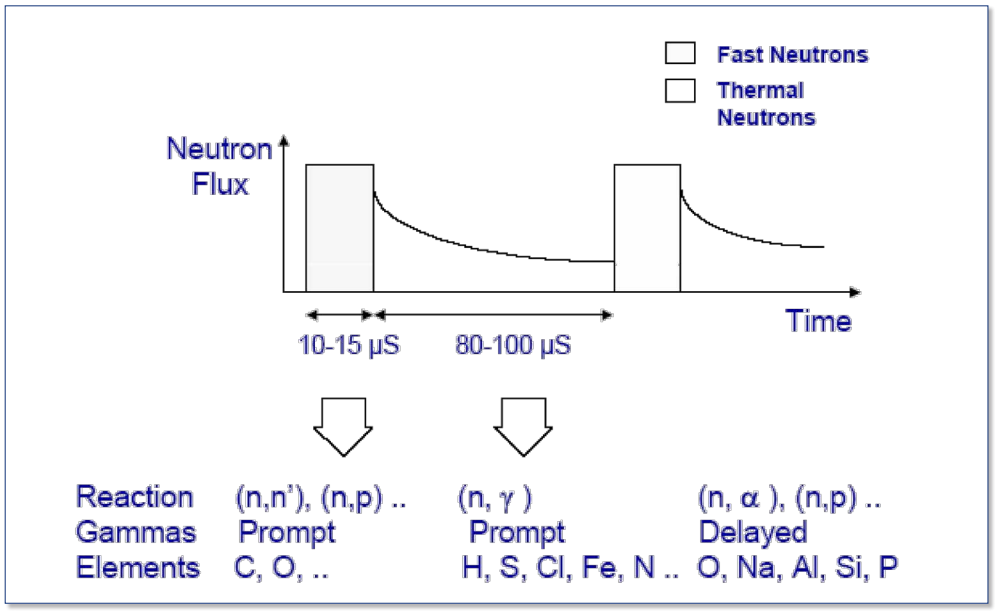



Figure 18: Pulse neutron generator time sequence

on and off, thus reducing radiation exposure concerns.

The advantages of thermal neutron activation are:

- Wide variety of applications. The penetrating nature of both the neutrons and the emitted gamma rays, which readily pass through most common materials (including metal), can be used in a wide variety of explosives detection applications including:
  - vehicle screening,
  - small cargo screening,
  - baggage inspection, and
  - detection of unexploded ordnance.
- High accuracy and low false alarm rate.

Figure 19: Example of a commercially available TNA systems (Rapiscan Systems)

Some of the disadvantages of thermal neutron activation are:

- Not suitable for personnel screening. Exposure to neutrons can have unacceptable health consequences.
- Not suitable for inspection of large cargo containers due to the technique's use of low- energy neutrons.
- General radiation exposure concerns.
- Thermal neutron analysis does not detect all kinds of explosive materials.
- High cost:
  - baggage screening cost is approximately $150,000
  - cargo screening cost is approximately $1,300,000
- Nitrogen-containing, non-explosive materials may set off alarms.


Figure 20: A monitor display showing an alarmed vehicle (Rapiscan Systems: thermal neutron activation "TNA®" and fast neutron activation system).

### 3.3.1 Fast Neutron Activation (FNA)

Fast neutron activation is a bulk detection technique in which an item or area to be screened for explosives is exposed to a high-energy stream of neutrons. The fast neutron interacts with the nucleus of matter under inspection and the neutron is absorbed and results in the emission of a high-energy gamma ray. Gamma ray emission occurs for carbon, nitrogen and oxygen. The technique is able to determine the type of substance under analysis. The neutron source used in a fast neutron activation system is provided by an electronic neutron generator and, as mentioned above, the neutron generator adds cost and experimental complexity to the system, but it has a safety advantage in that the stream of neutrons can be turned on and off, thus reducing radiation exposure concerns.

Use of a neutron generator also allows the instrument to function in pulsed mode, called pulsed fast neutron analysis (PFNA). With very short, nanosecond, pulses, it is possible to use time of flight information to locate the material.

Advantages of pulsed fast neutron activation are:

- Information is gathered on elements besides nitrogen, such as carbon and oxygen, which helps in explosives-like material determination.
- This technique has good neutron penetration and can be used on large cargo containers. Three-dimensional location information can be determined in the object of concern.

Disadvantages of pulsed fast neutron activation systems are:

- System complexity and high cost: a fixed location vehicle system costs over $5,000,000.
- Radiation and shielding concerns.

### 3.3.2 Pulsed Fast/Thermal Neutron Activation (PFTNA)

Pulsed neutron-based technique uses both fast neutron and thermal neutrons. Neutrons are pulsed at the nuclei of interest and characteristic gamma ray emission is collected. Pulsed fast/thermal neutron activation yields information on several elements including carbon, hydrogen, nitrogen, and oxygen.

Advantages of pulsed fast/thermal neutron activation are:

- Information is gathered on elements besides nitrogen, such as carbon and oxygen, aiding in the determination of explosives-like material.

Disadvantages of are

- System complexity, radiation and shielding concerns;
- No location information is obtained;
- Cost— the systems are more complex than the PFNA and need more complex detectors and image processing system.

### 3.3.3 Improvements of neutron-based techniques

The atomic ratio by itself is not a very reliable indicator of the presence of explosive, since a wide variety of explosives are in use (see section 5), including some which contain no nitrogen. In a security application such as baggage inspection the neutron beam interacts with the many different substances present and the indicated atomic ratios reflect this, making it hard to interpret. All of these neutron methods could be improved in several ways, such as by better γ or other detectors and better data processing to reduce the false alarm rate. For example, this would enable multidirectional beams or even three-D imaging. Neutron detection also can be usefully combined with X-ray imaging, to improve the detection statistics.

### 3.3.4 Associated particle imaging (API)

In a deuterium-tritium neutron generator an alpha particle is produced in association with each neutron.

D + T - > n + α

As a charged particle, the α may be located with a position-sensitive detector so that its direction of flight and time of emission may be measured. The associated neutron has the same time of emission and its direction of flight may be inferred by conservation of momentum, adding spatial information to the elemental composition information obtained from the γ measurements.

## 3.4 Threat image projection

As mentioned above, automatic monitoring of images is becoming feasible but, for the time being, a human operator monitoring the screen is still the norm. In most applications, it would be expected that a very large number of innocent items would pass the system for every item containing explosives. Threat Image Projection (TIP) is a method of ensuring that the operators remain alert for these very rare cases. At random intervals, the system displays an image of a threat-object: a bomb, gun, knife, narcotics package etc. selected at random from a library. On seeing a threat-object on an image, the operator acknowledges it to the system e.g. by pressing a button. If the threat has been projected from the library, the system confirms this to the operator who then proceeds with the next item to inspect. If the threat is in a real image, not from the library, the system gives the alarm. If the operator fails to acknowledge a library threat image, the system also indicates this. For example, a supervisor could then instruct the operator to increase concentration, take a rest break, or whatever other action is deemed appropriate.

# 4. Characteristics of explosives

Many different types of explosive exist and certain types may be more used by particular groups or at particular times, depending on availability, information etc. Currently, a particular danger is perceived from plastic and liquid explosives. The sources from which terrorists may acquire explosives are from the military, from industry and by making them themselves. Blocking terrorist acquisition of military and industrial explosives is dependent on the rigorous following of security procedures for storage, transport and use, including careful documentation. Technology, such as radio-frequency tracking devices, may also help. Prevention of illicit fabrication of explosives is currently a subject of significant attention. The main difficulties are that precursor materials are legitimately available and in widespread use, not only by industry but even as household chemicals, and recipes have been widely disseminated via the internet.

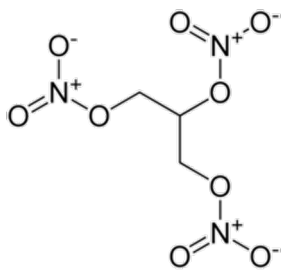
## 4.1 Plastic & liquid explosives

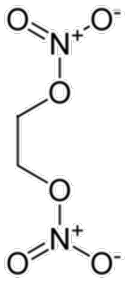
Energetic materials have several key characteristics (chemical, energetic, mechanical, etc.) In this section we will concentrate on two groups that have the biggest potential for illicit use, because of their mechanical characteristics: plastic and liquid explosives.

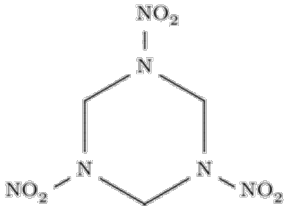
From the name of the group we can consider their main physical characteristics: Plastic explosive is high explosive that has added plasticizing material that makes it soft and hand-malleable and may have the added benefit of making it usable over a wider temperature range than pure explosive.

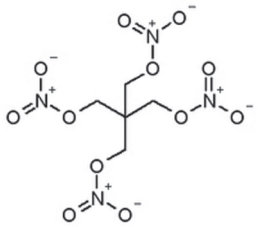
Liquid explosive is energetic material that is in the liquid phase and has the advantage that it can be put in various containers of different shapes and sizes. Liquid explosives are attractive to terrorists because of the scope they offer for disguising a bomb as an innocent beverage or foodstuff. The materials themselves are not in general novel or unusual. Liquid explosives are widely used in mining and quarrying for example, as are slurry explosives, saturated aqueous solutions of oxidizers and/or fuels. Nitroglycerin, one of oldest known high-explosives, is a liquid, as is nitroglycol, also known as ethylene glycol dinitrate (EGDN), a related compound with a lower freezing point. Nitroglycol was used in the March 11th 2004 attack on the Atocha Railway Station in Madrid.

## 4.2 Industrial and military explosives commonly used by terrorists

| NITROGLYCERIN | |
|---|---|
| Chemical: Propane-1, 2, 3-triyl trinitrate ($C_3H_5N_3O_9$)<br>Density: 1.13g/cm$^3$<br>Mainly industrial |  |

| NITROGLYCOL (EGDN) |  |
|---|---|
| Ethane-1,2-diyl dinitrate<br>$C_2H_4N_2O_6$<br>Density 1.49 g/cm$^3$<br>Mainly industrial | |

| RDX (cyclonite, hexogen) |  |
|---|---|
| Chemical: $C_3H_6N_6O_6$<br>Density : 1.82g/cm$^3$<br>Mainly military | |

| PETN (Penthrite) |  |
|---|---|
| Chemical: C $(CH_2ONO_2)_4$<br>Density: 1.773 g/cm$^3$<br>Both military and industrial | |

Mixtures of these explosives are important, one of the best known is Semtex:

| | H | A |
|---|---|---|
| **PETN -** | **49.8%** | **94.3%** |
| **RDX -** | **50 %** | **5.7%** |

(Dye, binder, Plasticizer)

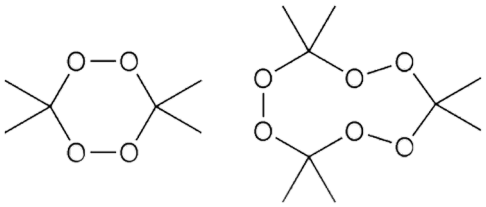
AMMONIUM NITRATE(AN)

AN based explosives are ordinarily stable and are widely used by legitimate industry and also by the military. Terrorist use is usually in the form of a very large vehicle bomb. Pure AN is hard to initiate so it is usually mixed with other substances. A common mixture is ANFO (Ammonium Nitrate Fuel Oil) . Others are AMONAL (mixed with aluminum powder), AMATOL(mixed with TNT) and AN/nitromethane mixture.

Chemical: $NH_4NO_3$
Density: (bulk) 0.840 g/cm$^3$

## 4.3 Home-made explosives

Amongst the home-made explosives, of greatest concern are the peroxide explosives. The best known is triacetone triperoxide, a substance relatively easily made from household chemicals. It cannot be detected by instruments designed to detect nitrogen because it does not contain any. TATP has been identified in explosive devices in a number of cases involving jihadist terrorists. Richard Reid, who attempted to down American Airlines Flight 63 in December 2001 with a bomb concealed in his shoe, the device containing plastic explosive with a TATP trigger. Homemade peroxide explosives were used in the July 7th 2005 attacks in London and TATP was found at the terrorist base in the Vollsmose quarter of Odense raided in 2006. Peroxide explosives are often dangerously unstable, and frequently kill their manufacturers or would-be users, so they are not used by industry, the military or financially-motivated criminals, but by fanatic terrorists, such as suicide bombers. The usual mode of terrorist use is man-carried, in rucksacks or belts.

| TATP | |
|---|---|
| Chemical:<br>$C_9 H_{18} O_6$<br>(trimer – triacetone triperoxide)<br>$C_6 H_{12} O_4$<br>(dimer – diacetone diperoxide)<br>Density: 1.27 g/cm$^3$ |  <br>Dimer Trimer |

**Home made AN-based**

Many terrorists attacks have employed homemade explosive mixtures based on fertilizer ammonium nitrate, notably Oklahoma City 1995, Omagh 1998 and Vollsmose-Odense 2006. Its particular threat is that it is readily and legitimately available in quantities of 100's of kg. AN is of considerable importance in agriculture, for which purpose no alternative is known which is as cheap, effective and environmentally benign. The European Fertilizer Regulation (EC) No. 2003/2003 restricts the concentration and forms in which AN can be sold, with a view to preventing accidental explosions. Voluntary control schemes also exist in some countries e.g. [20].

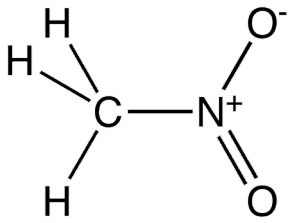
**Gunpowders and similar mixtures**

The other common class of home-made explosives is the oxidizing salt/fuel mixture type, which includes traditional gunpowder, based on potassium nitrate. Other oxidizers used are sodium chlorate and potassium chlorate and perchlorate. Although sometimes thought not as dangerous as the other substances listed here, this type of explosive has been used by terrorists in deadly attacks, including in Bali in 2002. Even when made by non-malicious amateur pyrotechnicians motivated by curiosity or entertainment, they can be dangerous. Accidents with them cause deaths in Europe each year.

## 4.4 Flammable liquid and propellants

Most of the liquid explosives are nitro compounds, organic compounds that contain one or more nitro groups $NO_2$, They are often highly sensitive: various impurities or improper handling can easily trigger a violent exothermic decomposition. Several kinds of liquid explosives are in common use as liquid propellants, including as standard military grade propellants (Table 4). The danger from these explosives is that they are likely to be in their final state, stored ready to use in drums, so that there is no need for a thief to extract them from munitions, like other kinds of

standard explosive.

| NITROMETHANE |  |
|---|---|
| HE (TNT) equivalents: 100%<br>Chemical: $CH_3NO_2$<br>Density: 1.138 g/cm$^3$ | |

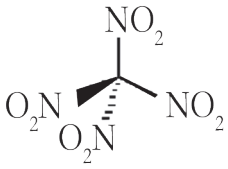
| TETRANITROMETHANE |  |
|---|---|
| HE (TNT) equivalents: 100%<br>Chemical: C $(NO_2)_4$<br>Density: 1.62294 g/cm$^3$ | |

Figure 21: Examples of liquid and shaped plastic explosives


Table 4: Liquid propellant - Military use [13]

**Liquid propellant HE (TNT) equivalents**

| Propellant combinations | Static test stands | Range launch |
|---|---|---|
| $LO_2/LH_2$ or $B_5Hg$ an oxidizer | 60% | 60% |
| $LO_2/LH_2$ and $LO_2$/RP-1 | Sum of 60% for $LO_2/LH_2$ plus 10% for $LO_2$/RP-1 | Sum of 60% for $LO_2/LH_2$ plus 20% for $LO_2$/RP-1 |
| $LO_2$/RP-1, $LO_2/NH_3$ or $B_5Hg$ and a fuel | 10% | 20% up to 500,000 pounds plus 10% over 500,000 pounds |
| IRFNA/Aniline | 10% | 10% |
| IRFNA/UDMH | 10% | 10% |
| IRFNA/UDMH plus JP-4 | 10% | 10% |
| $N_2O_4$/UDMH plus $N_2H_4$ | 5% | 10% |
| $N_2O_4$/UDMH plus $N_2H_4$ plus solid propellants | 5% plus the NEW of the solid propellants | 10% plus the NEW of the solid propellants |
| Tetranitromethane (alone or in combinations) | 100% | 100% |
| Nitromethane (alone or in combinations) | 100% | 100% |

## 4.4 IONIC LIQUIDS

Conventional liquid explosives are mostly molecular-based. Recently, the synthesis of three new families of heterocyclic-based ionic salts was undertaken and accomplished [16]. Three triazole systems, 1H-1,2,4-triazole, 4-amino-1,2,4-triazole, and 1H-1,2,3-triazole, were used as proton bases with nitric ($HNO_3$), perchloric ($HClO_4$), and dinitramidic ($HN(NO_2)_2$) acid systems. In all cases, stable salts were recovered and fully characterized by vibrational spectra (IR, Raman), multinuclear NMR spectroscopy, material balance, density measurements, and elemental analyses, as well as DSC, TGA and initial safety testing (impact). Many of these salts have melting points well below 100 °C, yet high decomposition onsets, defining them as new, highly energetic members of the well known class of materials identified as ionic liquids. Additionally, the single crystal X-ray diffraction study of 1, 2, 4-triazolium perchlorate was investigated, revealing the expected structure.

# 5. Research & Development financed by the European Commission

## 5.1 Introduction

The European Commission plan for its Seventh Framework Programme for research and technological Development (FP7) aims at Collaborative Research, based around broad research themes, rather than instruments, with much continuity from FP6 as well as the addition of two new topics, space and security.

The "European Security Research Advisory Board" (ESRAB) published in Sep. 2006 the European Security Research Agenda. Some key points from its summary are:

"Detection and identification capabilities represent a key area for EU investment over the coming years. A broad range of application as, detection of unattended luggage in open areas and the detection of dangerous goods (drugs, explosives and CBRN) where existing technologies are generally too bulky, too slow, and generate unacceptably high false alarm rates. Complementary capabilities, to be developed in parallel, relate to improving the identification and authentication of cooperative, or non-cooperative, individuals."

"Finally detection, identification and authentication capabilities need to be supported by appropriate localization and tracking capabilities for individuals and goods for a comprehensive approach towards potential threats."[11]

"Numerous independent but interrelated systems must be integrated and then demonstrated to prove operational effectiveness. In areas of significant European interest, it is recommended that demonstration programmers be established to act as federative frames to coalesce the required research."

ESRAB recommended five such programs:

- Aftermath crisis management;
- European-wide integrated border control system;
- Logistic and supply chain security, goods screening;
- Security of mass transportation;
- CBRNE - detection and identify of agents and devices.

ESRAB's analysis of the Border Security question focuses on technologies and capabilities to enhance the effectiveness and efficiency of all systems, equipment, tools and processes required for improving the security of Europe's land and coastal borders, including border control and surveillance issues.

The JRC's Border Security (BORSEC) Action includes as a topic work on capabilities in explosives and CBRN detection.

The work program for FP7 Theme 10 "security" published on 22.12.2006 includes most of the topics discussed.

In the year 2004 the EU launched the Preparatory Action on "Enhancement of the European Industrial Potential in the Field of Security Research 2004-2006" (PASR) which constitutes the Commission's contribution to the wider EU agenda

for addressing key security challenges facing Europe today. It focused in particular on the development of a security research agenda to bridge the gap between civil research ,as supported by EU framework programs, and national and inter-governmental security research initiatives . Security research from the year 2007, however, is supported by FP7.

During 2004-2006 there were three calls that in total cost 45 M€ to fund about 40 projects with the following defined priorities:

- "Improving situation awareness" (shorthand for surveillance and intelligence gathering);
- "Optimizing security and protection of networked systems";
- "Protecting against terrorism";
- "Enhancing crisis management"; and
- "achieving interoperability and integrated systems for information and communication" (shorthand for linking national and international law enforcement databases and information systems).

Synopses of each of the PASR projects may be downloaded from the Directorate General for Enterprise website at http://ec.europa.eu/enterprise/security/documents_en.htm

We collect here the projects that related to identification and explosive detection Previous Framework Programmes have also funded research and development projects on explosives detection, some of which we list overleaf. As well as projects intended to serve anti-terrorism and anti-organized-crime security applications, there were others directed towards post-conflict humanitarian needs, such as landmine and unexploded ordnance detection.

A searchable database of Framework Programme projects is publicly available on the EC's Community Research and Development Information Service (http://cordis.europa.eu) where more details may be found.

| CALL | PROJECT | PROJECT ID | CONTACT | START |
|---|---|---|---|---|
| PASR 2004 | TERASEC<br>Active Terahertz Imaging For Security | G.A. SEC4-PR-004000 | Dr. Heinz-Wilhelm Hübers<br>Deutsches Zentrum für Luft- und Raumfahrt e. V.<br>Heinz-Wilhelm.Huebers@dlr.de | 2005 |
| PASR 2004 | ESSTRT<br>European Security: High Level Study On Threats Responses and Relevant Technologies | G.A. SEC4-SA-003200 | Peter Munday<br>Thales Research and Technology Ltd<br>peter.munday@thalesgroup.com | 2004 |
| PASR 2004 | IMPACT<br>Innovative Measures For Protection Against CBRN Terrorism | G.A. SEC4-PR-008000 | Peter Van Hooft<br>TNO Defence, Security and Safety<br>hooft@pml.tno.nl | 2004 |
| PASR 2005 | PALMA<br>Protection Of Airliners Against Manpads Attacks | G.A. SEC5-PR-110800 | Gilles Fournier<br>gilles.fournier@eads.net | 2006 |
| PASR 2005 | PATIN<br>Protection Of Air Transportation And Infrastructure | G.A. SEC5-PR-110400 | klaus.scheerer<br>EADS CCR DCR/STI/T<br>Diehl BGT Defence<br>klaus.scheerer@diehl-bgt-defence.de | 2006 |
| PASR 2005 | PRISE<br>Privacy Enhancing Shaping Of Security Research And Technology –<br>A Participatory Approach To Develop Acceptable And Accepted Principles For European Security Industries And Policies | G.A. SEC5-SA-108600 | Johann Čas<br>Austrian Academy of Sciences<br>jcas@oeaw.ac.at | 2006 |
| PASR 2005 | SECCONDD<br>Secure Container Data Device Standardisation | G.A. SEC5-SA-105100 | Michael Naylor<br>Thales Research and Technology Ltd. UK<br>mike.naylor@thalesgroup.com | 2006 |
| PASR 2005 | SOBCAH<br>Surveillance of Border Coastlines and Harbours | G.A.SEC5-PR-102100 | Mario Audenino<br>Galileo Avionica SpA<br>mario.audenino@galileoavionica.it | 2006 |
| PASR 2006 | ISOTREX<br>Integrated system for on-line trace explosive detection in solid and vapour state | G.A. SEC6-PR-203600 | Antonio Palucci<br>ENEA Italy<br>palucci@frascati.enea.it | 2007 |
| PASR 2006 | STABORSEC<br>Standards for Border Security | G.A. SEC6-SA-210900 | Nicolas Delvaux<br>Sagem Défense Sécurité<br>nicolas.delvaux@sagem.com | 2007 |

Table 5:
European Commission funded projects relating to explosive detection: Preparatory Action on Security Research (PASR 2004 and 2005 and 2006)

Table 6: European Commission funded projects relating to explosive detection: FP4, 5, 6 & 7

| CALL | PROJECT | PROJECT ID | CONTACT | START |
|---|---|---|---|---|
| FP7 | IMSK - Integrated Mobile Security Kit | SEC-2007-218038 | Saab AB SWEDEN | 2008 |
| FP7 | EFFISEC - Efficient Integrated Security Checkpoints | SEC-2007-217991 | Sagem Défense Sécurité, FRANCE | 2008 |
| FP7 | CREATIF - CBRNE Related Testing and Certification Facilities | SEC-2007-217922 | Dr F Strebl, Austrian Research Centres | 2008 |
| FP7 | STRAW – Security Technology Active Watch | SEC-2007-218132 | Atos Origin SA SPAIN | 2008 |
| FP7 | UNCOSS – Underwater Coastal Sea Surveyor | SEC-2007-218148 | CEA, FRANCE | 2008 |
| FP7 | LOTUS – Location of Threat Substances in Urban Society | SEC-2007-217925 | Swedish Defence Research Agency | 2008 |
| FP7 | OPTIX – Optical Technologies for the Identification of Explosives | SEC-2007-218037 | Indra Sistemas SA, SPAIN | 2008 |
| FP6 | RESCUER - Improvement Of The Emergency Risk Management Through Secure Mobile Mechatronic Support To Bomb Disposal | IST-2002-511492 | Gusztáv Arz Budapest University of Technology and Economics | 2004 |
| FP6 | VERTIGO - Versatile Two Micron Light Source | IST-2005-034692 | Marcel Rattunde Fraunhofer Gesellschaft Zur Foerderung Der Angewandten Forschung E.V. | 2006 |
| FP6 | TERANOVA - Novel Terahertz Sensing and Imaging Systems for Biotechnology, Healthcare, Security and Process Monitoring | IST-2002-511415 | Giles Davis University of Leeds | 2004 |
| FP6 | EURITRACK - European Illlicit Trafficking Countermeasures Kit | IST-2002-511471 | Jean-Louis Szabo CEA Saclay | 2004 |
| FP6 | DETEX - Development of a “Tandem” chemosensor system based on both highly selective and highly sensitive innovative materials: Application to ultra-trace detection of Explosives | NMP-2002-505908 | Céline Fiorini CEA Saclay | 2004 |
| FP6 | GOSPEL - European Network of Excellence in Artificial Olfaction | IST-2002-507610 | Udo Weimar University of Tübingen | 2002 |
| FP5 | EXPLO-NOSE - Multi-technique control system for the detection of hidden explosives | G6ST-CT-2001-50066 | Sergio Cantino C.M.C. Consulenze Metallurgiche E Controlli S.R.L. | 2001 |
| FP5 | NUPULSE - A non-destructive pulse neutron multiple detector tool for use in environmental, hydrocarbon and mineral exploration work | G1RD-CT-2002-00714 | Raimo Matikainen Geological Survey of Finland | 2002 |
| FP5 | BioSens - Vapour dEtEctION - Area reduction in demining | IST-2000-25348 | Stephen Crabbe Statens Raeddningsverk | 2001 |
| FP5 | NOSE II - Second Network on Artificial Olfactory Sensing | IST-2001-32494 | Udo Weimar, Mika Harbeck University of Tübingen | 2001 |
| FP4 | NOSE - Artificial olfaction - development of sensors, arrays and olfactory imaging systems | ESPRIT 29526 | Wolfgang Göpel University of Tübingen | 1999 |
| FP4 | Searcher - an instrument to detect and identify organic substances in inaccessible places | SMT 4965012 | John Francis Caunt John Caunt Scientific Ltd. | 1996 |
| FP4 | TINA - Detection And Location Of Concealed Plastic Explosive In On-Line Baggages Screening By Tomographic Interrogation By Neutron Assaying | IN30937I | Peter Choi X-Technologies Ecole Polytechnique | |
| FP4 | FLEXSECURE - Modular, scalable detection system for explosives, drugs and weapons in hand baggage and medium sized parcels Project Acronym | ESPRIT 23480 | Rainer Henkel Heimann Systems | 1997 |

# 6. European legislation and policy concerning explosives and EDS

Explosives and equipment connected with them are the subject of several European laws and policies. Much of the acquis communautaire in this area is not concerned with malicious use but pertains to safety and regulation of trade. This reflects the fact that security lay outside the jurisdiction of the EU institutions until the establishment of the Common Foreign and Security Policy and Justice and Home Affairs Pillars under the Maastricht Treaty of 1992. New policy initiatives in explosives security have been undertaken in this field over the last few years which are focused much more on prevention of terrorist and criminal use.

## 6.1 The Dangerous Substances Directive

Council Directive 769/1976 (EEC) established a framework for harmonizing legislation concerning dangerous substances across the member states. It has been repeatedly amended and consolidated to address more substances, mainly toxic and flammable substances. At present, explosives are not covered by it but an amendment to cover ammonium nitrate is currently being considered.

## 6.2 The Explosives Directive

Council Directive 93/15/EEC (on the harmonization of the provisions on the placing on the market and supervision of explosives for civil uses) is concerned with safety requirements for explosives and security controls on their transfer. Following on from this, Commission Directive 2008/43/EC provides for setting up a system for identification and traceability

## 6.3 The Aviation Security Regulations

In March 2008, the old European Aviation Security law, Regulation (EC) 2320/2002 of the Parliament and Council, was repealed and replaced by Parliament/Council Regulation (EC) No. 300/2008. It constitutes the EU's interpretation of Annex 17 of the Chicago Convention on International Civil Aviation, which is the basic instrument of international law in this field. A key change concerning explosives detection is that the new Regulation allows Hold Baggage not to be re-screened when it has arrived from another Member State or from a country outside the EU which has equivalent security standards.

Unlike the old Regulation, the new Regulation does not go into any detail concerning equipment, stating simply that "Equipment used for screening, access control and other security controls shall comply with the defined specifications and be capable of performing the security controls concerned", and there is no Annex stating prohibited items. The purpose of this change is to avoid the need to go through a lengthy political process if any updates are required for purely technical reasons.

Some details are currently covered by Commission Regulations as tabulated below. Several of these include technical Annexes which are classified Secret. Their general topics are public, being stated in the Implementation Reports COM(2005)428 and COM(2007)542. Under the new regime of Regulation 300/2008, it is intended that these measures will be repealed and replaced Commission Decisions. These need not be published in the Official Journal, eliminating the need for a separate Secret Annex.

| COMMISSION REGULATION | SUBJECT |
|---|---|
| 622/2003 | Implementation measures, Annex with details of prohibited articles |
| 1217/2003 | Common specifications for national civil aviation security quality control programs. |
| 1486/2003 | Procedures for Commission inspections |
| 68/2004 | Amends Annex of 622 on prohibited articles |
| 1138/2004 | Definition of security restricted areas of airports, Screening of staff |
| 781/2005 | Amends Annex of 622, performance standards for X-ray machines |
| 857/2005 | Amends Annex of 622, hand search of passengers |
| 65/2006 | Procedures for evaluation and introduction of new technical methods and processes |
| 240/2006 | Amends Annex of 622, vehicles entering secure area |
| 831/2006 | Amends Annex of 622, rules on air cargo security |
| 1448/2006 | Amends Annex of 622, performance standards for EDS |
| 1546/2006 | Amends Annex to 622, adds restrictions on liquids [23] |
| 1862/2006 | Amends Annex to 622, performance standards for walk through metal detectors |
| 358/2008 | Amends Annex to 622, removes restrictions on cabin bag size |

## 6.4 Maritime Security Regulations

Regulation (EC ) No. 725/2004 of the European Parliament and Council is aimed at enhancing the security of ships used in international trade and domestic shipping and associated port facilities. It provides a basis for the harmonized interpretation and implementation and Community monitoring of the International Maritime Organisation's Safety of Life at Sea (SOLAS) Convention and International Ship and Port Facility Security (ISPS) Code. SOLAS includes a requirement to prevent the introduction of unauthorized weapons, incendiary devices or explosives to ships or port facilities and also to conduct assessments of the effect of explosives on ship and port structures. Ports covered by ISPS must have a Port Facility Security Plan which should include the use of scanning/detection equipment, mechanical devices or dogs, with training drills for staff. Directive 2005/65/EC places a duty on Member States to identify specific requirements for dealing with established security concerns, such as 'suspect' cargo, luggage, bunker, provisions or persons, unknown parcels and known dangers (e.g. bombs) when conducting the Port Security Assessments required by ISPS.

## 6.5 The Fertilizer Regulation

The Fertilizer Regulation (EC) 2003/2003 of the Parliament and Council contains provisions regarding explosive hazards concern the risk of accidental explosions, rather than terrorist acts. It defines test methods in detail.

## 6.6 The Seveso II Directive

Council Directive (EC) 96/1982 concerns safety of fixed installations storing large quantities of dangerous substances.

## 6.7 ADR/ADN and their EU Implementation

Recommendations covering the transport of dangerous goods, including hazardous wastes and substances, are issued and regularly revised by the Committee of Experts on the Transport of Dangerous Goods of the United Nations Economic and

Social Council which has its secretariat in the United Nations Economic Commission for Europe (UNECE). These recommendations serve as the basis for many national regulations a well as for international instruments covering the transport of dangerous goods by sea, air, rail, road and inland waterways all over the world. Amongst these, those listed below have also been developed and are regularly updated by the UNECE.

1. European Agreement concerning the International Carriage of Dangerous Goods by Road ( ADR), of 30 September 1957
2. Protocol amending article 1 (a), article 14 (1) and article 14 (3) (b) of the European Agreement of 30 September 1957 concerning the International Carriage of Dangerous Goods by Road ( ADR), of 28 October 1993
3. Convention on Civil Liability for Damage caused during Carriage of Dangerous Goods by Road, Rail and Inland Navigation Vessels ( CRTD), of 10 October 1989
4. European Agreement concerning the International Carriage of Dangerous Goods by Inland Waterway ( ADN), of 25 May 2000

ADR requires that dangerous goods, including specifically explosives, which are transported by road are packaged and labeled in an agreed manner and the vehicles satisfy certain rules regarding their construction, equipment and operation. ADR is applied inside the EU by Council Directive 94/55/EC, Directive 2000/61/EC of the European Parliament and the Council and Commission Directive 2003/28/EC.

## 6.8 COTIF/RID and its EU implementation

The Convention concerning International Carriage by Rail (COTIF) has an Annex called the Regulations concerning the International Carriage of Dangerous Goods by Rail (RID). RID was brought into force in the EU through Directive 96/49 and updated every two years in line with updates of RID. The latest was in 2007 through Directive 2006/ 90.

A new Framework Directive 2008/68/EC of September 2008 will simplify the structure for EU implementation of ADR, ADN and COTIF/RID.

## 6.9 REACH

Parliament and Council Regulation (EC) 2006/1907, Registration, Evaluation, Authorisation and Restriction of Chemicals Regulation (REACH), is an extremely complex law which concerns production and use of chemical substances. Its purpose is to ensure a high level of human health and environmental protection.

REACH requires explosive properties to be stated as standard information in documentation for any substance manufactured or imported in bulk.

## 6.10 European Council Declaration of 25th March 2004, and revised action plan

In response to the Atocha Railway Station bombing the European Council issued a Declaration on Combatting Terrorism, to which was Annexed a revised Plan of Action with updated strategic objectives. In this statement the Council recognized the need to ensure greater security of firearms, explosives and bomb making equipment.

In COM(2004)698 Communication from the Commission to the Council and the European Parliament on Prevention, preparedness and response to terrorist attacks, the Commission stated that it was actively pursuing these objectives with the research community, experts, the European Police organization EUROPOL and the explosives and detonator manufacturers.

## 6.11 COM(2005)329

In the Communication from the Commission on measures to ensure greater security in explosives, detonators, bomb-making equipment and fire-arms (COM(2005)329), the Commission described actual and planned measures and stated its will to engage in a structured dialogue with the private sector and its intention to set up an expert group.

## 6.12 Public-private security dialogue

The Commission organized a conference entitled Public-Private Security Dialogue: Detection Technologies and Associated Technologies in the Fight against Terrorism in Brussels in November 2005. The following September it issued COM(2006)474 "Green Paper on detection technologies in the work of law enforcement, customs and other security authorities" which was presented in the form of questions, intended to elicit responses from public and private sector stakeholders.

The Commission, led by its Directorate General for Justice, Liberty and Security (DG JLS), duly established the expert group which it had earlier suggested during its security of explosives conference in January 2007. Around 100 experts representing the relevant public and private stake-holders participated in the ESETF under four working groups:
WG1 – Precursors
WG2 – Supply Chain
WG3 – Detection
WG4 – Public Security Aspects
ESETF's findings were brought together in a report [22] which was released at a conference held in Braga, Portugal in July 2007.

ESETF made 56 specific recommendations. In response, the Commission defined an Action Plan, which was submitted to the Council of the EU and the European Parliament. The Justice and Home Affairs Council of 6th and 7th December 2007 approved the Strategic Orientations and Priority Measures of the Action Plan and also designated within each of the areas "Prevention", "Detection", "Preparedness and Response" and "Horizontal Measures" certain measures as constituting priorities. Amongst these priorities were two committees to be established: an ad hoc group on detection and a standing committee on precursor materials. The latter was convened for the first time on 30th January 2008. EUROPOL is setting up a database of known offences involving explosive use and another Council priority is the upgrading of this database to allow European government agencies secure access at all times.

## 6.13 Standards for EDS

PASR project STABORSEC revealed a need for further work on specification and certification standards for explosive detection equipment in Europe, since at present they are poorly developed. Two US standards were identified:

ASTM F792-01e2
Standard Practice for Evaluating the Imaging Performance of Security X-Ray Systems

BSR N42.40-200x (DRAFT STANDARD)
Standard for Evaluation and Performance of High-Energy, X-Ray Interrogation Systems for Detection of Contraband of concern in Homeland Security

STABORSEC recommended that minimal detection thresholds and classification be agreed amongst member states. For EDS in airports, this has already been addressed by Commission Regulation 1448/2006 (see above), but it does not apply to land or maritime borders. Moreover, even for aviation there is no standardized protocol for test and evaluation. Each laboratory has different methods of assessing whether the instrument has achieved the statutory performance requirements, and they may give conflicting answers.

STABORSEC also recommended making specifications for data format and image quality to facilitate exchange of X-ray etc. images of bombs amongst States.

JRC is currently maintaining the website http://staborsec.jrc.it where the STABORSEC reports ("Deliverables") may be downloaded and the recommendations read in full.

# 7. Glossary

## 7.1 Definitions

**Bulk explosives-detection equipment**
Any explosives detection device or system that remotely senses some physical or chemical property of an object under investigation to determine if it is an explosive.

**CBRN**
Chemical, biological, radiological and nuclear, used to describe a weapon or threat

**EDS**
Explosive detection system is a means of detecting the presence of explosives, in either trace or bulk quantities, typically employing some combination of electronic sensors, software and/or chemical reagents. Sniffer dogs or other animals may also be considered part of an EDS.

**Fast neutrons**
Have energy greater than 1 eV, 0.1 MeV or approximately 1 MeV, depending on the definition.

**FNA**
Fast Neutron Analysis.

**Ion mobility spectrometer (IMS)**
A means to identify substances based on the different ability of molecular ions to move through a low pressure gas. IMS utilizes the following four steps (1) vaporize the sample, (2) ionize the vapor (place an electric charge on sample molecules), (3) accelerate the ions using an electric field (4) pass the ions through a drift space filled with low pressure gas and determine the number of separated ions arriving after different time intervals. The pattern of separation is compared to a library of known patterns to identify the substance collected.

**Mass spectrometry (MS)**
A means to identify substances based on charge-to-mass ratio. MS utilizes four steps: (1) vaporize the sample, (2) ionize the vapor (3) separate the ions using an electric or magnetic field, and (4) determine the number of separated ions having a particular charge-to-mass ratio. The uniqueness of mass spectrometry lies in its chemical specificity. It directly measures a fundamental property of the target molecule—its molecular weight—and thus provides a highly specific means of identifying the molecule. Some forms of MS use a more energetic ionization which breaks the molecules so that fragments may also be seen. MS has inherently better specificity than IMS, since different molecules may have similar IMS drift times.

**Nuclear magnetic resonance**
A bulk explosives detection technique based on the magnetic properties of the hydrogen atoms within the explosive being detected.

**Nuclear quadrupole resonance**
Induces nuclei of specific atoms to store RF energy for a short time.

**Particulate**
Refers to microscopic particles of solid material that adhere (contaminate) to surfaces That have, directly or indirectly, come into contact with an explosive material.

**Plastic explosives**
Are high-explosive materials that have the general consistency of plastic. They are usually based on RDX and/or PETN. Examples include C-4, Detasheet, and Semtex.

**Pulsed fast neutron analysis**
A nuclear-based screening technique that measures the elemental composition of the object being scanned through neutron interaction with elemental constituents of the object, resulting in characteristic gamma rays.

**Sensitivity**
The ability of the detector to identify explosives if an explosive is present.

**Slow neutrons**
Have energy less than 1 eV.

**Specificity**
The ability of the detector to identify explosives only if an explosive is present.

**Thermal neutrons**
Have an average energy of about 0.025 eV.

**Time-of-flight (TOF) mass spectrometer**
Ionized sample molecules in a vacuum are accelerated in a straight line so that they fly down an evacuated tube. By measuring how long the ions take to reach a detector at a fixed position and by taking into account the length of the flight, one can determine the mass-to-charge ratio and the number of ions detected at each sequential mass.

**Trace explosive**
Detection consists in the chemical identification of microscopic residues of the explosive compound, either in vapor or in particulate form. Vapor refers to the gas-phase molecules emitted from the explosive's surface (solid or liquid) because of its finite vapor pressure.

**Validation**
Confirmation that the specified requirements (for an explosives-detection system) satisfy stakeholder needs.

**Vapor pressure**
All solids and liquids emit a certain amount of vapor (usually have correlation with temperature) and that the pressure of the gas phase above them. Sometime expressed as relative concentrations in saturated air, rather than in true pressure units, and are usually expressed in units of ppm (parts per million: 1:106 , corresponding to one molecule per one million air molecules), ppb (parts per billion, 1:109), or ppt (parts per trillion, 1:1012 ).

## 7.2 Abbreviations

| | |
|---|---|
| ANFO | Ammonium Nitrate in Fuel Oil |
| CARS | Coherent anti-Stokes Raman spectroscopy |
| DIAL | Differential Absorption Light Direction and Ranging |
| DIRL | Differential reflectance LIDAR |
| DMDB | Dimethylnitrobenzene |
| DNT | Dinitrotoluene |
| ECAC | European Civil Aviation Conference |
| EDS | Explosive detection system |
| EGDN | Ethylene glycol dinitrate (also called nitroglycol) |
| ETD | Explosive traces detectors |
| HMX | High Molecular weight RDX – a name for cyclotetramethylenetetran itramine (acronym sometimes explained as Her Majesty's Explosive, High Melting Point Explosive etc.) |
| IMS | Ion Mobility Spectrometer |
| LIDAR | Light Direction and Ranging |
| LIBS | Laser-induced breakdown spectroscopy |
| MMW | Millimeter Wave |
| NG | Nitroglycerine |
| NT | Nitrotoluene |
| PETN | Pentaerythritol tetranitrate |
| PFTNA | Pulsed Fast Thermal Neutron Analysis |
| ppb | Parts per billion |
| ppm | Parts per million |
| ppt | Parts per trillion |
| $PS^3$ | Personal Security Screening System |
| RDX | Research Department Explosive – a name for cyclotrimethylenetrinitramine |
| SPF-FD | Surface laser Photo Fragmentation - Fragment Detection |
| TATP | Triacetone triperoxide |
| TNA | Thermal Neutron Analysis |
| TNT | Trinitrotoluene |
| TOF | Time-of-flight |

# 8. References

[1] Jehuda Yinon, 1999, Forensic and Environmental Detection of Explosives, New York: John Wiley & Sons.

[2] Claudio Bruschini,2001, Commercial Systems for the Direct Detection of Explosives. École Polytechnique Fédérale de Lausanne (EPFL) & Vrije Universiteit Brussel.

[3] Jehuda Yinon, 2007, Counter Terrorist Detection Techniques of explosives Elsevier.

[4] National Materials Advisory Board, 2004, Opportunities to Improve Airport Passenger screening with Mass Spectrometry.

[5] The National Academies Press, 2004, Existing and Potential Standoff Explosives Detection Techniques. http://www.nap.edu/.

[6] Lisa Theisan, Ph.D. David W. Hannum Dale W. Murray John E. Parmeter, 2004, Survey of Commercially Available Explosives Detection technology and Equipments.

[7] C. L. Rhykerd, D. W. Hannum, D. W. Murray, J. E. Parameter, Guide for the Selection of Commercial Explosives Detection Systems for Law Enforcement Applications, NIJ Guide 100-99, National Institute of Justice, Office of Science and Technology, Washington, DC 20531, September1999, NCJ 178913. http://virlib.ncjrs.org/LawEnforcement.asp.

[8] National Research Council,(2002), Summary -- Assessment of the Practicality of Pulsed Fast Neutron Analysis for Aviation Security, http://www.nap.edu/catalog/.

[9] Drake, G.; Hawkins, T.; Brand, A.; Hall, L.; McKay, M.; Vij, A.; Ismail, I. Propellants, Explosives, Pyrotechnics 2003, 28, 174-180.

[10] Reports OTA-ISC-481 (1991) and OTA-ISC-511 (1992), S Congress, Office of Technology Assessment, Washington, DC, USA.

[11] B. J. Micklich, B. P. Curry.,C. L. Fink, D. L. Smith and T. J. Yule, System design considerations for fast-neutron interrogation systems Engineering Physics Division, Argonne National Laboratory 9700 South Cass Avenue, Argonne, Illinois 60439 USA.

[12] Meeting the challenge: the European Security Research Agenda A report from the European Security Research Advisory Board, (2006), ISBN 92-79-01709-8.

[13] Army Pamphlet 385-64 Ammunition and Explosives Safety Standards, Department of the Army, Washington, DC 15 December 1999.

[14] V. Valkovic, A Feasibility Study of Landmines Detection using 14 MeV Neu-

trons, in Application of Nuclear Techniques to Anti-Personnel Landmines Identification, Report of the First Research Co-ordination Meeting held 23-26 Nov. 1999 at the Rudjer Boškovic Institute in Zagreb, Croatia, IAEA publication IAEA/PS/RC-799. Contact.

[15] Pulsed Fast/Thermal Neutron Analysis: A Technique for Explosives Detection Kouropoulos and P. C. Womble Applied Physics Institute, Western Kentucky University, Bowling Green, KY 42101.

[16] Drake, Greg ; Hawkins, Tommy ; Brand, Adam ; Mckay, Milton ; Ismail, Ismail, Energetic, Low Melting Salts of Simple Heterocycles, Air Force Research Lab., Edwards AFB, CA. Space and Missile Propulsion Div.

[17] Kurt J. Linden, William R. Neal Terahertz Laser Based Standoff Imaging System Spire Corporation klinden@spirecorp.com, University of Massachusetts Lowell.

[18] Novak, D.; Waterhouse, R.; Farnham, A. "Millimeter-wave weapons detection, System", Applied Imagery and Pattern Recognition Workshop, 2005. Proceedings. 34th Volume , Issue , 19-21 Oct. 2005.

[19] A.Buffler .Using Fast Neutron to Detect Explosive and Illicit Material, Department of Physics, University of Cape Town, Rondebosch, 7701, South Africa.

[20] Secure Your Fertilizer National Counter Terrorism Security Office www.secureyourfertilizer.gov.uk.

[21] Ion Mobility Spectrometry by Gary Alan Eiceman and Zeev Karpas, 1994, (cited on http://www.smithsdetection.com/).

[22] Enhancing the Security of explosives, Report of the explosives security experts task force European Commission Directorate General for Justice, Freedom and Security, Brussels 28.06.2007.

[23] New Security Rules at Airports, A Brief Guide to Help You, European Commission, Association of European Airlines and Airports Council International Europe, 2006 http://ec.europa.eu/transport/air_portal/security/rules_liquids/doc/2006_aviation_security_new_rules_poster_en.pdf

[24] Anna Petersson, Sara Wallin, Birgit Brandner, Carina Eldsäter and Erik Holmgren Explosives Detection – A Technology Inventory FOI-R—2030—SE ISSN 1650-1942 FOI Defence Research Agency, Tumba, Sweden, September 2006

[25] S. A. Brink. Bofors Schnauzer-a biosensor for detection of explosives The Detection of Abandoned Land Mines: A Humanitarian Imperative Seeking a Technical Solution, EUREL International Conference (Conf. Publ. No. 431) ISBN 0 85296 669 5 Edinburgh 7-9 Oct 1996 Page(s):33 - 36

[26] J R Webster, KV Pearson, D B Chang, N L Moise and V Vali X-ray fluorescence imaging of elements US Patent 4987582 (1991)

[27] L.S. Ettre, J. Chromatogr. Sci. 16, 396–417 (1978)

# 9. APPENDIXES

| Explosives Based on Nitrogen | Formula | wt % C | wt % H | wt % N | wt % O | Sum N + O |
|---|---|---|---|---|---|---|
| Ammonium nitrate (AN) | $H_4N_2O_3$ | 0 | 5.04 | 35.01 | 59.97 | 94.98 |
| Ammonium picrate (Expl D) | $C_6H_6N_4O_7$ | 29.28 | 2.46 | 22.76 | 45.5 | 68.26 |
| Cyclonite (RDX) | $C_3H_6N_6O_6$ | 16.22 | 2.72 | 37.84 | 43.22 | 81.06 |
| Ethylenediamine dinitrate | $C_2H_{10}N_4O_6$ | 12.91 | 5.42 | 30.1 | 51.58 | 81.68 |
| Guanidine nitrate | $CH_6N_4O_3$ | 9.84 | 4.95 | 45.89 | 39.32 | 85.21 |
| Hexamethylenetriperoxide diamine (HMTD) | $C_6H_{12}N_2O_6$ | 34.62 | 5.81 | 13.46 | 46.11 | 59.57 |
| Hexanitrohexaazaisowurtzitane (HNIW or CL20) | $C_6H_6N_{12}O_{12}$ | 16.45 | 1.38 | 38.36 | 43.82 | 82.18 |
| Hydrazine nitrate | $H_5N_3O_3$ | | 5.3 | 44.2 | 50.09 | 94.29 |
| Mannitol hexanitrate | $C_6H_8N_6O_{18}$ | 15.94 | 1.78 | 18.59 | 63.69 | 82.28 |
| Monomethylamine nitrate | $CH_4N_2O_3$ | 13.05 | 4.38 | 30.43 | 52.14 | 82.57 |
| Nitrocellulose | $C_6H_7N_3O_{11}$ | 24.24 | 2.37 | 14.14 | 59.23 | 73.37 |
| Nitroglycerin (NG) | $C_3H_5N_3O_9$ | 15.87 | 2.22 | 18.5 | 63.41 | 81.91 |
| Nitrotriazolone (NTO) | $C_2H_2N_4O_3$ | 18.47 | 1.55 | 43.08 | 36.9 | 79.98 |
| Octogen (HMX) | $C_4H_8N_8O_8$ | 16.22 | 2.72 | 37.84 | 43.22 | 81.06 |
| Pentaerythritol tetranitrate (PETN) | $C_5H_8N_4O_{12}$ | 19 | 2.55 | 17.72 | 60.73 | 78.45 |
| Picric acid | $C_6H_3N_3O_7$ | 31.46 | 1.32 | 18.34 | 48.88 | 67.22 |
| Tetrazene | $C_2H_8N_{10}O$ | 12.77 | 4.29 | 74.44 | 8.5 | 82.94 |
| Tetryl | $C_7H_5N_5O_8$ | 29.28 | 1.76 | 24.39 | 44.58 | 68.97 |

Table 7: Some nitrogen-based high explosives and their compositions

| Name | Molecular Weight | C | H | N | O | Density ($g/cm^3$) | Vapour Pressure (rel. \| Torr) | Preferred Trace Det. |
|---|---|---|---|---|---|---|---|---|
| **TNT** | 227.13 | 7 | 5 | 3 | 6 | 1.65 | 7.7 ppb \| $5.8 \cdot 10^{-6}$ (25 °C) | Particle (Vap.) |
| **RDX** | 222.26 | 3 | 6 | 6 | 6 | 1.83 | 6.0 ppt \| $4.6 \cdot 10^{-9}$ (25 °C) | Particle |
| **HMX** | 296.16 | 4 | 8 | 8 | 8 | 1.96 | 3.95 ppt \| $3 \cdot 10^{-9}$ (100 °C!) | Particle |
| **Tetryl** | 287.15 | 7 | 5 | 5 | 8 | 1.73 | 7.5 ppt \| $5.7 \cdot 10^{-9}$ (25 °C) | Particle |
| **PETN** | 316.2 | 5 | 8 | 4 | 12 | 1.78 | 18 ppt \| $1.4 \cdot 10^{-8}$ (25 °C) | Particle |
| | | | | | | | | |
| **NG** | 227.09 | 3 | 5 | 3 | 9 | 1.59 | 0.41 ppm \| $3.1 \cdot 10^{-4}$ (26 °C) | Vapour |
| **EGDN** | 152.1 | 2 | 4 | 2 | 6 | 1.49 | 92.6 ppm \| 0.07 (25 °C) | Vapour |
| | | | | | | | | |
| **AN** | 80.05 | – | 4 | 2 | 3 | 1.59 | 12 ppb \| $9.1 \cdot 10^{-6}$ (25 °C) | Particle (Vap.) |
| **TATP** | 222.23 | 9 | 18 | – | 6 | 1.2 | | |
| | | | | | | | | |
| **DNB** | 168.11 | 6 | 4 | 2 | 4 | 1.58 | 3.8 ppm \| $2.9 \cdot 10^{-3}$ (25 °C)* | |
| **Picric acid** | 229.12 | 6 | 3 | 3 | 7 | 1.76 | 7.6 ppt \| $5.8 \cdot 10^{-9}$ (25 °C)* | |

Table 8: Summary of physical and chemical properties of common explosives [1] [6]

Figure 22: Nitrogen density of common materials and explosives [10]

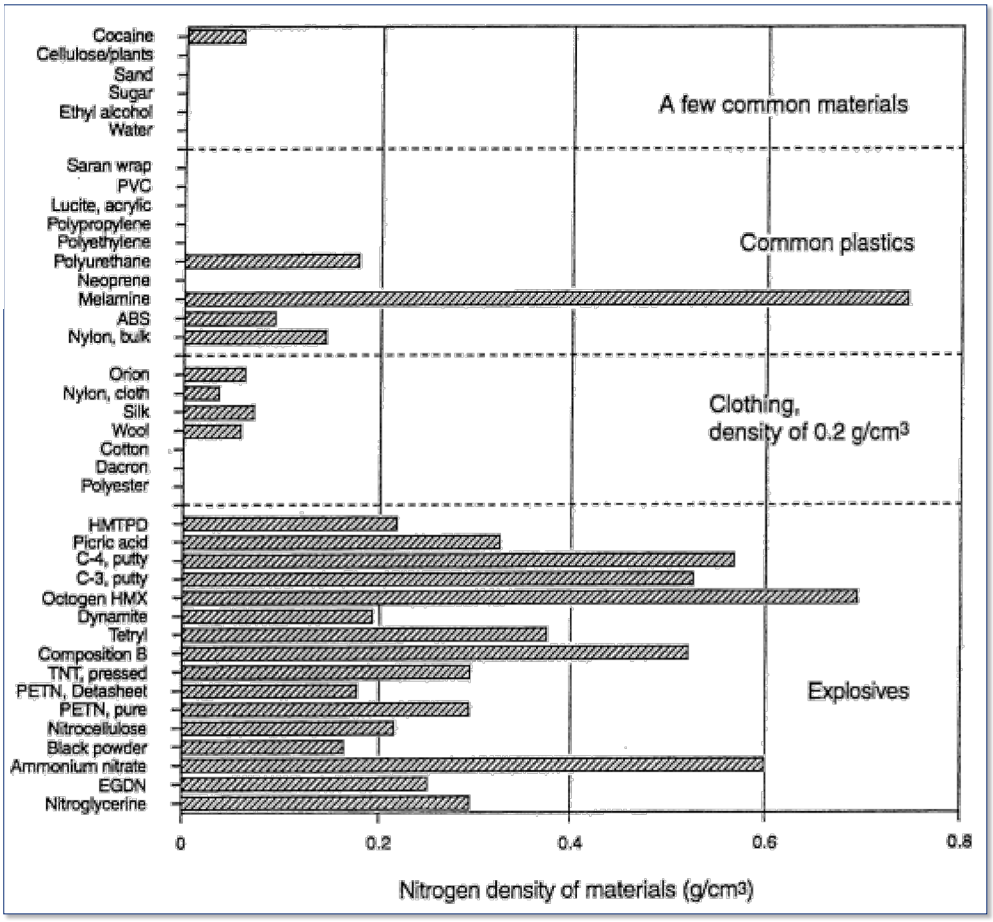



Figure 23: Vapor pressures of high explosives and additives. [4]

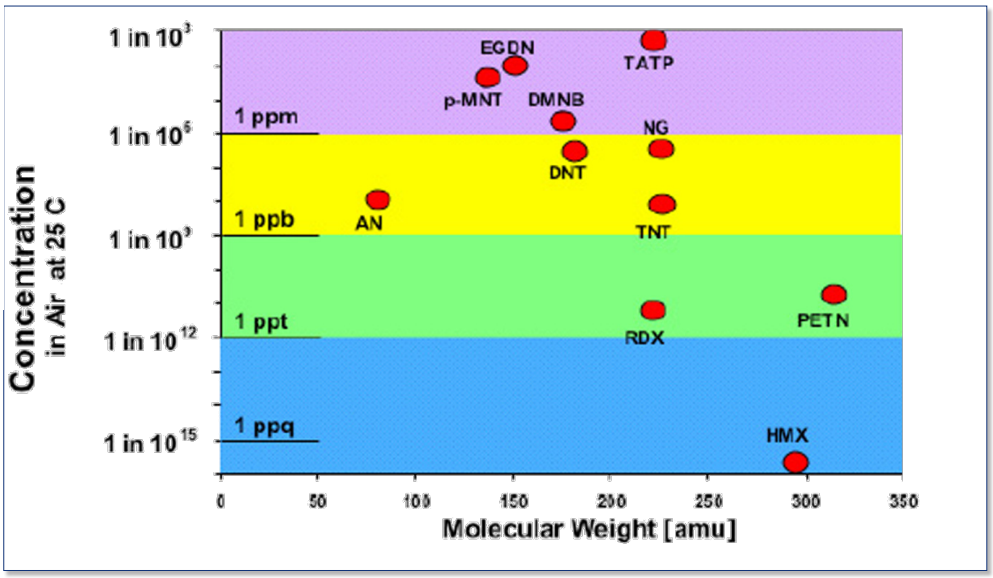


Table 9: Vendor List for Commercially Available Bulk Explosives Detection Technologies

| Company | Phone Number | Web Address | Address | Main Equipment/ Technology/uses |
|---|---|---|---|---|
| 3DX-RAY Ltd. | +44 1664 503600 | www.3dx-ray.com | Pera Innovation park, Nottingham Road Melton Mowbray, Leicestershire,LE13 0PB UK | X-Ray (Hand carried package) |
| American Science and Engineering, Inc. (AS&E) | +1 978-262-8700 | www.as-e.com | 829 Middlesex Turnpike Billerica, MA 01821, USA | X-Ray: Transmission & double sided Z backscatter |
| Autoclear | +1 973-276-6161 | www.controlscreening.com | 2 Gardner Rd Fairfield, NJ 07004, USA | X-Ray: Dual-Energy (mail &fixed and mobile vehicle search and personal) |
| Bruker Daltonics | +1 978-663-3660<br>+49 (421) 2205-0 | www.bdal.com | • 40 Manning Rd Billerica MA 01821, USA<br>• Fahrenheitstr. 4 D-28359 Bremen FRG | TNA |
| Delta X-ray | +1 703-820-5204 | www.delta-xray.com | 2111 Wilson Blvd, Suite 700 Arlington, VA 22201 USA | X-Ray: Portable (limited for personal) |
| G E Security (inc. former InVision and Quantum Magnetics) | +1-888-437-3287 | www.gesecurity.com | 8985 Town Center Parkway Bradenton, FL -34202-5129 USA | X-Ray (CT and XRD), NQR (Baggage ,Hand carried package, shoes) |
| Gilardoni | +39 0341 705111 | www.gilardoni.it | Via Arturo Gilardoni 1, 23826 Mandello Del Lario, Lecco ITALY | X-Ray (Baggage ,Hand carried package) |
| Golden Engineering Inc. | +1 765-855-3493 | www.goldenengineering.com | PO Box 185,Centerville, IN 47330 USA | X-Ray: Portable (limited for personal) |
| L3 Communications Security & Detection Systems | +1 781-939-3800 | www.dsxray.com | 10E Commerce Way Woburn, MA 01801, USA | X-Ray: Dual-Energy& Computed Tomography, millimeter wave (Packages, Baggage and hand carried ,Cargo& Vehicle (Mobile)) |
| Logos Imaging | +1 765-939-4044 | www.logosimaging.com | P.O. Box 765 Richmond, IN 47375, USA | X-Ray: Portable (limited for personal) |
| Reveal Imaging | +1 781-276-8400 | www.revealimaging.com | 201 Burlington Rd Bedford, MA 01730 USA | CT X-Ray, Baggage, and hand carried inc. larger bags, mobile |
| Q R Sciences Ltd. | +618 9351 1200 | www.qrsciences.com | 8-10 Hamilton street, Cannington WA 6107 AUSTRALIA | X-Ray, NQR (Baggage, Hand carried package) |
| Rapiscan Systems | +1 310-978-1457<br>+44 (0)870-7774301 | www.rapiscan.com | 2805 Columbia St. Torrance CA 90503, USA<br>X-Ray House Bonehurst Road, Salfords Surrey RH1 5GG UK | X-Ray: single energy Dual-Energy & Diffraction and high energy (Packages, Baggage, and hand carried ,Cargo Container and Vehicle) |
| Science Application International Corporation (SAIC) | +1 800-962-1632<br>+1 866-723-8726 | www.saic.com/products/security | Security & Transportation Technology 10260 Campus Point Drive, San Diego, CA 92121, USA | X-Ray: Portable (limited for personal). Gamma ray: Vehicle, Cargo |
| SAS R&D Services | 954-432-2345 | www.sasrad.com | 2714 SW 183rd Ave. Miramar, FL 33029, USA | Gamma Backscatter (Baggage, Handheld) |
| Scanna MSC Ltd | +44 20 7355 3555 | www.scanna-msc.com | 223 Regent Street, London W1B 2EB, UK | X-Ray Portable (limited for personal) |
| • Smiths Detection (inc. former Barringer, ETG, Graseby)<br>• Smiths Heimann GmbH. | +44 (0)1923 294400<br>+49 611 9412 0 | www.smithsdetection.com<br>www.smith-heimann.com | 459 Park Avenue Bushey Herts. WD23 2BW UK<br>Im Herzen 4 65205 Wiesbaden, FRG | X-Ray: Dual-Energy (Hand carried package, Cargo& Palletized Cargo and Vehicle) |

Table 10: Vendor List for Commercially Available Trace ExplosivesDetection Technologies (Used for Personnel, package, and vehicle search)

| Company | Phone Number | Web Address | Address | Detector types* |
|---|---|---|---|---|
| Biosensor Applications Sweden AB | +46 (0) 8 706 75 00 | www.biosensor.se | Solna Strandväg 3 SE-171 54 Solna SWEDEN | Immunological/ micromechanical |
| Bruker Daltonics | +1 978-663-3660 +49 421 2205-0 | www.bdal.com | • 40 Manning Rd Billerica MA 01821, USA • Fahrenheitstr. 4 D-28359 Bremen FRG | GC/MS |
| CDEX Inc | +1 520-745-5172 | www.cdex-inc.com | CDEX, Inc., 4555 S. Palo Verde, Suite 123 Tucson, AZ 85714, USA | UV fluorescence |
| Constellation Technology Corporation | +1 727-547-0600 | www.contech.com | 7887 Bryan Dairy Road Largo, FL 33777-1452, USA | GC/MS |
| Electronic Sensor Technology | +1 805-480-1994 | www.estcal.com | 1077 Business Center Circle, Newbury Park, CA 91320, USA | GC/SAW |
| GE Security (formerly GE Ion Track) | +1 978-658-3767 | www.gesecurity.com | 205 Lowell Street Wilmington, MA 01887, USA | ITMS (IMS based) |
| Mass Spec Analytical Ltd | +44 117 3173600 | www.msaltd.co.uk | Building 20F Golf Course Lane, PO Box 77, Filton, Bristol BS99 7AR, UK | Portable tandem MS |
| Mistral Security Inc | +1 301-913-9368 | www.mistralgroup.com | 7910 Woodmont Ave, Suite 820, Bethesda, MD 20814, USA | Color |
| Scintrex Trace Corp. (subsidiary of Autoclear) | +1 613-224-1061 | www.scintrextrace.com | 300 Parkdale Ave. Ottawa, Ontario, Canada K1Y 1G2 | CL, TR, GC-IMS/CL |
| Smiths Detection (inc. former Barringer, ETG, Graseby) | +44 1923 294400 | www.smithsdetection.com | 459 Park Avenue Bushey Herts. WD23 2BW UK | IMS |
| Thermo Scientific (formerly Thermo Electron) | +1 203 605 2534 | www.thermo.com/security | 148 Old Gate Lane Milford CT 06460, USA | GC/DMS (IMS based) |

* A detector types
CL: chemiluminescence
DMS: differential ion mobility spectrometry
GC: gas chromatography
IMS: ion mobility spectrometry
ITMS: ion trap ion mobility spectrometry
MS: mass spectrometry
NDLM: non linear dependence of ion mobility
SAW: surface acoustic wave
TR: thermo-redox

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Abstract
This report contains a brief survey of Explosives Detection Technology, as it is applied for inspection of goods and passengers at borders, and explains the role of European legislation and the European Commission's research programs in this field. It describes the techniques of trace and bulk explosives detection that are in use, the latest techniques that are in development and the characteristics of explosives that are, or might be, used to provide a signature for exploitation in detection technology. References to academic reviews are included for those wishing to study the subject in greater depth. Some additional details are given concerning plastic and liquid explosives, which are a threat of particular current importance. The report also contains a brief account of relevant European trade, safety and security legislation, a description of recent policy initiatives and tables of related European Commission funded research projects. Contact details of commercial companies selling explosive detection products are also provided.

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